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Study and simulation of waveforms for 5G systems.

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Table of Contents

Abstract

The impact of digital communications has marked the beginning of a new era in the world. The expansion of the network of networks called the Internet has been beyond almost everyone expectations. Digital data continues to grow and with it, the need of new means of communication between all kind of devices. This new ways to be connected to the Internet consolidate the importance of the wireless communication systems. The content within the network is also evolving to multimedia data with the demand of data transfer speed and quality that it carries. Because of the rise of this data demand, the mobile networks have to play a very important role in keeping up with their technologies and the growth of users around the world.

The control of the mobile network development falls on the International Telecommunication Union (ITU) and the two partnerships who adapt the technology as the world evolves. This organizations were formed to establish a transition to the third generation of mobile communications, each one of them related to a different standard. Their name were a consequence of their purpose: Third Generation Partnership Project (3GPP and 3GPP2). Now a days these organizations keep on dictating the evolution of the wireless communication systems and recently made the transition to a fourth generation communication with a common standard adopted by both partnerships: LTE (4G).

Wireless communications' future is set on the next generation: the fifth. The new waveform for the 5G is being decided in this very moment and can affect the development of the next technologies. The final goal of every new generation is to improve the performance of the previous ones and to be able to do that, experiment around the actual models to find out the better solution for the new system seems necessary. With that said, the established system use an Orthogonal Frequency-Division Multiplexing (OFDM) to modulate the data sent through the air which is the waveform that is being experimented on.

OFDM systems are based on the orthogonality principles of the signals. Sending each modulated symbol (usually BPSK, QPSK or QAM modulations) using a different frequency sine signal and combining every signal. This theory allows to identify every carrier frequency in the combine signal resulting in a demodulation of the symbols. The easiest way to perform this operation is creating a complex signal which represents the frequency domain and contain the modulated symbols (I/Q) placed in the spectrum alongside guard carriers. Using the algorithm Inverse Fast Fourier Transform (IFFT) the system creates the samples of a discrete time domain signal which form the OFDM symbol. In the transmission step each OFDM symbol is preceded by a Cyclic Prefix: the final samples of itself are placed at the beginning of the symbol. The OFDM symbol becomes larger to facilitate the demodulation step with the guard period of time given by this added samples.

The discrete time samples are directly related to the bandwidth of the signal in terms of sampling period. The signal travels through the channel in analogic terms so it is critical to adjust the bandwidth to match the LTE standard. Once the signal is sent it has to pass through two types of channels, one attached with the multi-path signal that reach the reception point: the power and delay of every path of the different transmission site. The other one is attached to the thermal noise of the equipment on the stations. The importance of the sampling period

comes in the relation to the delay samples of these multi-path channel models that have to adapt the taps to a discrete sample of the time domain signal. The channel models have to match the LTE standard to use the system in the closest case to the real performance.

Extended Pedestrian A model (EPA)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	0.0
2	30	-1.0
3	70	-2.0
4	90	-3.0
5	110	-8.0
6	190	-17.2
7	410	-20.8

Extended Vehicular A model (EVA)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	0.0
2	30	-1.5
3	150	-1.4
4	310	-3.6
5	370	-0.6
6	710	-9.1
7	1090	-7.0
8	1730	-12.0
9	2510	-16.9

Extended Typical Urban model (ETU)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	-1.0
2	50	-1.0
3	120	-1.0
4	200	-0.0
5	230	-0.0
6	500	-0.0
7	1600	-3.0
8	2300	-5.0
9	5000	-7.0

Figure A – LTE channel models

The thermal noise is inherent to every transmitted signal and is strictly related to its power. This channel is an Additive White Gaussian Noise (AWGN) that deteriorate the signal using a normal distribution with zero mean and the noise power as variance. The value of Signal-to-Noise Ratio establish a relation of power, but in digital communication this relation is usually measured by the Bit energy to noise ratio (E_bN_0). This value becomes signal power using the bits of the modulation and the OFDM characteristics.

The performance of the system within the multi-path channel depends on the dynamic adaptation to it. During this simulation the channel does not change while the transmission is being made, because of that, the channel is estimated at the beginning of the process. Synchronizing both ends of the system, it can send useless data through the channel to analyze the response and then use it to estimate the error cause by the channel. The system can use multiple OFDM symbols to avoid the effect of the random noise by using a mean of the correction to each symbol. This method allows the transmission to be fixed in the demodulation process. The estimation is also affected by the AWGN channel so it can cause error in the calculated correction.

The demodulation step of the signal apply the correction to the carriers of each OFDM symbol. The Cyclic Prefix is ignored when the process is reversed. The OFDM symbols' original samples pass through a Fast Fourier Transform (FFT) block to obtain the spectrum and the carrier value to demodulate. Because of the cyclic properties of the signal, the samples discarded can be the first ones as well as the last ones, leaving the symbol with the same information in every case. The carriers pass through the estimated correction and then begins the demodulation process. The extracted symbols' accuracy depend on the channel conditions and the result is usually displayed in the form of a constellation diagram with the value of Bit Error Rate (BER). This figures show the original position of each symbol and the actual position of the received ones in the In-Phase/Quadrature (I/Q) complex space.

Once the reference of the actual signal is complete, the next step is the development of the experimental systems and their designs. The first modification of the OFDM modulation avoids the use of redundant information in the Cyclic Prefix of the symbol replacing it with zero value samples. In other words, a tail of zeros the same length as the Cyclic Prefix. The OFDM Zero

Tail is built following the previous system steps having to adapt the different parts of the system to incorporate the Zero Tail. The creation of the signal is easiest than before, once the OFDM symbol is created it only takes adding some zeros at the end of it. The cyclic characteristic of the previous system is gone and in the reception step it cannot discard any samples to build the OFDM symbol. At the same time the channel estimation methods has to adapt as well to the new waveform accounting the zero samples to estimate the carriers' correction.

The next experimental system is attach to this last waveform and the modifications surrounding the Fourier Transform blocks of the transmission system. This report only analyze this model within the waveform generation stand point, it leaves the design of the whole system to further projects. The new OFDM symbol is created by two IFFT blocks instead of one. The first block transform the useful information, then the time domain zeros are added to the signal and it passes through a FFT block resulting in a new signal spectrum. This new spectrum is remapped to add the guard carriers and transformed again in the next IFFT block. The main difficulty of the transmission of this signal is the output samples of each IFFT block. It results in a signal with the same samples as the OFDM symbol without Cyclic Prefix but it contents the added Zero Tail. This waveform also have a few zero samples at the beginning of the symbol, the number of the header samples plus the tail samples are the same length as the Cyclic Prefix.

The MATLAB source code of this project becomes the test environment to these systems. Every design translate to a code to implement their characteristics in a low-pass model simulation: without using a central frequency and subcarriers placed in the electromagnetic spectrum. The first MATLAB model is the standard OFDM with Cyclic Prefix. Using different functions, the simulation covers all the steps of the system: Channel estimation, Modulation, Transmission, Reception and Demodulation. Along this source code goes the development of the simulation of the channel: the multi-path LTE channel and the AWGN channel.

The results have to be validated by creating known models to compare to them, in this case the validation process includes an M-QAM simulation and its theoretical bit error rate and a noise free multi-path channel to test the system's channel estimation. Using the first validation method it can be shown that the curves E_bN_0 vs BER of the systems (Theoretical, M-QAM and OFDM) are similar enough to considerate it as a valid model. In the last case the results are reflected in the constellation diagram of the OFDM system when using any multi-path channel, the received symbols are exactly the sent ones.

The MATLAB model of the OFDM CP is aim to be as changeable as possible. Following the commented source code any person with a medium knowledge of this program can adjust the parameters of the simulation to test any situation. This parameters are in the code section INPUT DATA where the system can be configured:

- M = Number of QAM symbols of the constellation
- Number of carriers
- Number of data carriers
- Number of OFDM symbols to send
- Length of the Cyclic Prefix

- Length of the Zero Tail
- Number of OFDM symbols to estimate the channel
- Bit energy to noise ratio (E_bN_0) [dB]
- Bandwidth [Hz]
- Single-path/Multi-path channel model

The following OFDM system models are based on this structure and all of them share the input data generated with this parameters.

The source code is organized in three scripts:

- The *simulation.m* script is the result of all the system's steps. With the properly configuration of the input data parameters the script represents the received information that has passed through the channel and the correction block. Using a common input data this script is used to compare the OFDM CP and the OFDM ZT models in particular situations. The result of this code comes in the form of BER value and constellation diagrams to display the performance in each case.
- The *simulation_BER_curves.m*, its name is clear enough, calculates the different BER of the systems using a group of E_bN_0 values. It is based on the previous script so the two systems can be test in more than a particular situation. The result becomes a graphic figure comparing the performance of each system with different noise ratios. This curves also include the validation methods of M-QAM and the theoretical result using the noise values.
- The *simulation_DFTs.m* is focus in the Discrete Fourier Transform spread concept. This code do not implement the whole system, its only purpose is compare the transmission waveforms of the two previous systems and the OFDM DFT-spread ZT model. The input data is still shared between the three systems with the complication that the DFT-spread model uses less information symbols in the generated transmission. Because of that, it discard the last symbols that do not fit in the algorithm. The results of this script are the comparison between the three waveforms and the three spectrums.

Testing the systems using a single-path channel the results show that the performance without channel estimation is almost identical between the two models. Adding the channel estimation to the equation the results show the importance of the number of symbols used to estimate; the systems response is closer to the previous result when more symbols to estimate are used. This means that in a single-path channel scenario the channel correction is affected by the noise and cause degradation in the results that can be improve adding more symbols to the estimation process.

Introducing the multi-path channel models to the systems the results without the channel estimation are wrong and the demodulation is not a representative result. Therefore the channel estimation is needed and even using it the results are not close to the AWGN theoretical ones. However, the figures shows similarity between the OFDM systems representing a slightly better performance in the OFDM CP systems. The OFDM CP perform equal or sometimes better than the OFDM ZT which lead the study to develop the next step in the evolution of the Zero Tail based systems.

The next results of the simulation represent the three systems, including the OFDM DFT-spread ZT transmission. Comparing the three wave forms the figure shows the effect of the second IFFT block on the zero samples of the new model. The real improvement comes in the spectrum of the three waveforms. While the OFDM CP and OFDM ZT have a similar frequency response, the new model improve the power of the shoulders with the disadvantage of using less real data carriers to fill the same bandwidth.

This spectrum improvement mean better performance with adjacent channels in the electromagnetic spectrum. The cost of this performance is low, it only takes to insert zero samples, which mean little modifications in the actual systems to achieve this performance. The next step for this system would be the simulation of the whole system design with the appropriate estimation channel method. This idea can be used for future projects using this source code as reference for the previous models to complete the results given by this new waveform.

1 Introduction

This report represents the last and most important document I have made during my time in the university. The main idea that surrounds all this work is the elaboration of a source code by a student for students. Because of that, the simulation is based in MATLAB and oriented to be as changeable as possible to allow people with a medium knowledge of this program to understand and modify it.

The initial step of this project is the simulation of an Orthogonal Frequency-Division Multiplexing (OFDM) system and its later validation. The system applies the fundamental orthogonality principles of the signals and creates a multiple carrier waveform including a modulated symbol in each carrier. This systems are usually in a certain central frequency with established bandwidth in the frequency spectrum. In this case the situation is a low-pass equivalent simulation only to see the waveform and error results of the modulation/demodulation process.

The motivation for this report comes from the implementation of the 5G network in mobile communication and the uncertainty of the new OFDM waveform. There are two systems that have real chances to become the new waveform: Zero Tail based OFDM and Filter Bank Multicarrier based OFDM. The 5G networks are the immediate future for mobile communications and their development has to be in the hands of the system performance instead of the different companies' interest. To be impartial developing this new systems requires an academic point of view in favor of the better solution possible for the new mobile networks.

The aim of this simulation is to be able to compare this new systems with a working model of the standard OFDM. In this report it was only possible to study and analyze the Zero Tail based OFDM leaving the rest for future projects.

However the simulation goal is to be as adaptable as possible, the channel models implemented in the source code are Long Term Evolution (commonly known as 4G) because of the drive of this new OFDM waveforms. The ideal situation to this experiments would be working with the 5G channel models (which are not decided yet), but it would be accurate enough to start with the already established ones.

2 Report Structure

This paper goal is to guide the reader throughout the analysis and the simulation of the mobile networks and their waveforms. The content of this report has been collected and written for a period of six months during my fifth year in the university. The MATLAB simulation becomes the pivotal point of this work, but it needs to be supported by the previous study of the different systems.

First of all comes the situation and context of this investigation. By a brief study of the actual mobile networks the future systems become the technology to work and study around in the telecommunication field. This development is carried by a number of organizations that dictate the controlled evolution of the networks through the years.

The next step represents the study of the different systems that the simulation is going to implement. This is a critical analysis to understand the source code and be able to modify it to test different situations. It is not only a study of the modulation systems, the channel between the modulation and the demodulation is also analyzed within this systems designs.

Using schemes of the different MATLAB script with their functions this paper display the possible modifications of all the systems models. At the same time, establish the results that each script can offer.

The final part comes in the form of MATLAB figures analyzing the simulation results and their advantages or disadvantages between systems. This study leads to the conclusion of the different simulation models and their performance.

Finally, the time table of this report can be divided in numerous tasks. All of this it is shown in the following figure as a Gantt chart along with the approximated dates of each part of the project:

Task name	Duration	Start	Finish
Research about OFDM systems	12 days	Sat 01/11/14	Sat 15/11/14
Definition of simulation milestones	17 days	Fri 14/11/14	Sun 07/12/14
Research about mobile networks	73 days	Sun 07/12/14	Tue 17/03/15
OFDM systems analysis	15 days	Mon 05/01/15	Fri 23/01/15
MATLAB code for OFDM model	43 days	Fri 23/01/15	Tue 24/03/15
Validation methods for the simulation	21 days	Tue 24/02/15	Tue 24/03/15
Simulation of LTE channel model	4 days	Tue 24/03/15	Fri 27/03/15
OFDM Zero Tail system design	2 days	Fri 27/03/15	Mon 30/03/15
MATLAB code for OFDM Zero Tail model	7 days	Mon 30/03/15	Tue 07/04/15
Comparative study	31 days	Tue 07/04/15	Tue 19/05/15
OFDM DFT-spread Zero Tail system design	4 days	Tue 19/05/15	Fri 22/05/15
MATLAB code for OFDM DFT-spread Zero Tail model	6 days	Fri 22/05/15	Fri 29/05/15
Simulation results	9 days	Fri 29/05/15	Wed 10/06/15
Systems' schemes	3 days	Wed 10/06/15	Fri 12/06/15
Report draft	21 days	Tue 19/05/15	Tue 16/06/15
Report final version	4 days	Tue 16/06/15	Fri 19/06/15

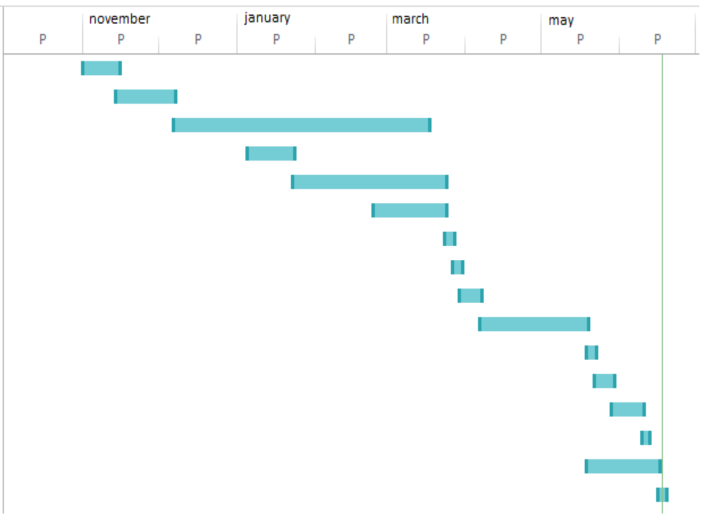

Figure 2.A – Gantt chart

3 Mobile Networks

In the last ten years of the past century the world suffered the equivalent of a new industrial revolution with the expansion of the Internet. This new era meant new ways of working and communicating with each other. Around the first years of this century the Internet stopped being a computer-to-computer massive network and started to affect in every aspect of life itself. The recent expansion of smartphones and tablet devices marks the beginning of the concept "Internet of things (IoT)" which extends the connections between every possible device. By 2020, it is estimated a total of 20 billion connected devices [1].

A lot of these new connections come in portable devices which represent the expansion of wireless communication networks. Alongside this growth comes the evolution of the multimedia content in the net that leaves speed connectivity obsolete in a period of three years or less. This is causing wireless networks to improve at a high ratio to match the content demand, rising the mobile networks at the front of innovation. Since the start of this new era mobile communications have been evolving [1]:

1G	First Generation	no data rate
2G	Second Generation	100 – 400 Kbit/s
3G	Third Generation	0.5 – 5 Mbit/s
4G	Fourth Generation	1 – 50 Mbit/s

In 1992 the European Telecommunications Standard Institute (ETSI) developed the GSM standard to be the deployed wireless service in the new radio network. In 1995 Qualcomm develop another standard to compete in the market: the IS-95. This service was mainly deployed in North America and was not compatible with GSM devices and vice versa.

3.1 Third Generation Partnership Project (3GPP)

In the year 1998 the need of a worldwide wireless communication system was critical and the members of the two previous standards formed two global partnerships (3GPP for GSM and 3GPP2 for IS-95) to establish the next generation networks. This organizations exist now a days and their mission is to meet the standard performance set by the International Telecommunication Union (ITU) choosing their respective technology [1]:

Generation	Organization	Release
2G	3GPP	GSM
	3GPP2	IS-95 (cdmaOne)
2.5G, 2.75G	3GPP	GPRS, EDGE (EGPRS)
	3GPP2	CDMA2000
3G	3GPP	UMTS
	3GPP2	CDMA 2000 1x EV-DO Release 0
3.5G, 3.75G, 3.9G	3GPP	HSPA, HSPA+, LTE
	3GPP2	EV-DO Revision A, EV-DO Revision B, EV-DO Advanced
4G	3GPP	LTE-Advanced, HSPA+ Revision 11+

Figure 3.1.A – 3GPP development

As it shows the previous figure the 3GPP2 lack 4G standard, the LTE-advanced and HSPA+ are the extended standard for the 4G mobile networks.

Release	Date	Summary
99	1999	First release of the UMTS standard
4	2001	Introduced an all-IP core network
5	2002	Introduced High-Speed Packet Downlink Access (HSDPA)
6	2004	Introduced High-Speed Packet Uplink Access (HSUPA)
7	2007	Introduced High-Speed Packet Access Evolution (HSPA+)
8	2008	Introduced new LTE System Architecture Evolution (SAE)
9	2009	Improvements to SAE and WiMAX interoperability
10	2010	Introduced 4G LTE-Advanced architecture

Figure 3.1.B – 3GPP releases

Release	Date	Summary
Rel. 0	1999	First release of the 1x EV-DO standard
Rev. A	2001	Upgrade to peak data-rate, lower latency, and QoS
Rev. B	2004	Introduced multicarrier capabilities to Rev. A
Rev. C	2007	Improved core network efficiency and performance

Figure 3.1.C – 3GPP2 releases

3.2 Long Term Evolution (LTE)

This standard is meant to be the future for all the mobile networks. This technology will be able to cover the demand of high data transmission speed using new design of the radio networks [1].

- All IP core network
- Simplified network architecture to lower costs
- Low latencies in user (<10 ms) and control planes (<100 ms)
- New radio interface and modulation for high throughput (100 Mbps)
- Ability to use larger bandwidth allocations and carrier aggregation
- MIMO as a requirement for all devices

The new networks design comes with a mayor capital investment at the doors of the leading communication companies. The cost of the LTE technology is slowing the transition process of GSM to LTE but every organization is set to accomplish these new radio networks within the next five years.

3.3 Evolved High-Speed Packet Access (HSPA+)

The 3GPP HSPA+ standard represents the intermediate step between 3G and 4G. This technology allows the current radio network to reach high-speed data transmission. While the LTE networks expand, this standard becomes a much cheaper version to improve the mobile communications by adapting the existing systems.

The lack of inversion on LTE networks has caused the massive expansion of this standard which is leading the world into the 4G.

3.4 Long Term Evolution Advanced (LTE-Advanced)

Once the expansion of LTE systems becomes worldwide the radio network will be able to adapt to the new developed standard. The LTE-Advance marks the line between 4G and 5G mobile communications [1].

	HSPA+	LTE	LTE-Advanced
Peak downlink speed (Mbit/s)	168	300	3,000
Peak uplink speed (Mbit/s)	22	75	1,500
Maximum MIMO streams	2	4	8
Idle to connected latency (ms)	< 100	< 100	< 50
Dormant to active latency (ms)	< 50	< 50	< 10
User-plane one-way latency (ms)	< 10	< 5	< 5

Figure 3.4.A – HSPA+ vs LTE vs LTE-Advance

LTE-Advance is still in the making and there are several technologies being considered. Within this development appears the new modulation schemes of Filter Bank Multicarrier and the Zero Tail based OFDM systems.

4 Orthogonal Frequency-Division Multiplexing

4.1 Description

Orthogonal Frequency-Division Multiplexing (OFDM) systems are based in the orthogonality principle of sine signals.

A system formed by functions:

$$\varphi_0\ (x), \varphi_1\ (x), \varphi_2\ (x), \dots, \varphi_n\ (x)$$

This system is orthogonal between [a , b] if:

$$\int_a^b \varphi_n\ (x)\ \varphi_m\ (x)\ dx = 0 \quad (n\ \neq m;\ n, m = 0,1,2, \dots)$$

At the same time has to verify that:

$$\int_a^b \varphi_n\ (x)\ \varphi_m\ (x)\ dx \neq 0 \quad (m = n)$$

$$\int_a^b \varphi_n^2\ (x)\ dx \neq\ 0 \quad (n = 1,2,3, \dots, k)$$

By these means we achieve a system formed by trigonometric functions which is an orthogonal system in any 2π length interval:

$$1\ , \cos x\ \ , \sin x\ \ , \cos 2x\ \ , \sin 2x\ , \dots, \cos nx\ , \sin nx\ ; \quad (n = 1,2,3, \dots, k)$$

Using this kind of system we can send each symbol in a different carrier frequency without interferences between them.

4.2 Transmission

The first step in building any digital communications system is modulate the data that is going to be transmitted. The most extended way to modulate digital data is using complex data, each part of the number is modulated using different orthogonal functions which results in two vectors of information: In-phase/Quadrature.

4.2.1 Quadrature Amplitude Modulation (QAM)

Assigning concrete values to the amplitude of these two vectors we can create a constellation in this two dimension space (I/Q) to understand the modulated data. Each pair of values I/Q equals a symbol. If the symbols are equally probable there has to be the same distance between them so the random noise cause the same error ratio in every symbol. In other words, the decision area of each symbol must be the same. It explains itself with an example:

4-QAM Alphabet	{ (± 1 ± 1j) }
16-QAM Alphabet	{ (± 1 ± 1j) , (± 1 ± 3j) , (± 3 ± 3j) , (± 3 ± 1j) }

64-QAM Alphabet { (± 7 ± 7j) , (± 7 ± 5j) , (± 7 ± 3j) , (± 7 ± 1j) , (± 5 ± 7j) , (± 5 ± 5j) , (± 5 ± 3j) , (± 5 ± 1j) , (± 3 ± 7j) , (± 3 ± 5j) , (± 3 ± 3j) , (± 3 ± 1j) , (± 1 ± 7j) , (± 1 ± 5j) , (± 1 ± 3j) , (± 1 ± 1j) }

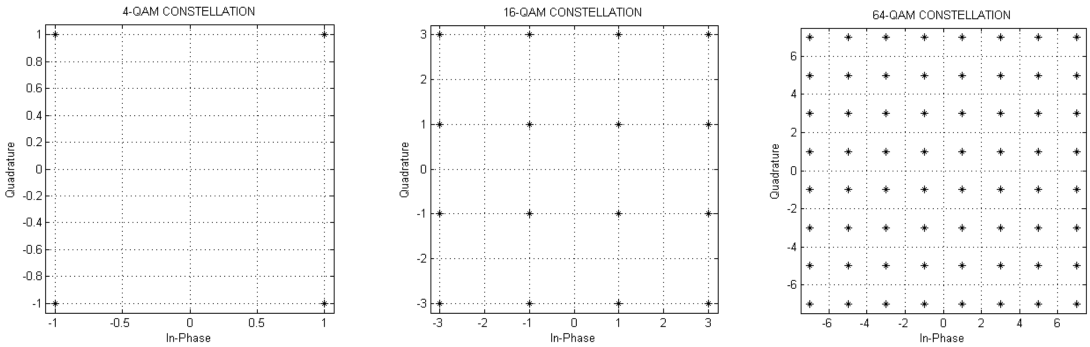

Figure 4.2.1.A – M-QAM Constellations

This modulations are usually coded with Gray Code. Using this code the symbols are mapped to guarantee that every symbol only distinct itself from the nearest ones in one bit:

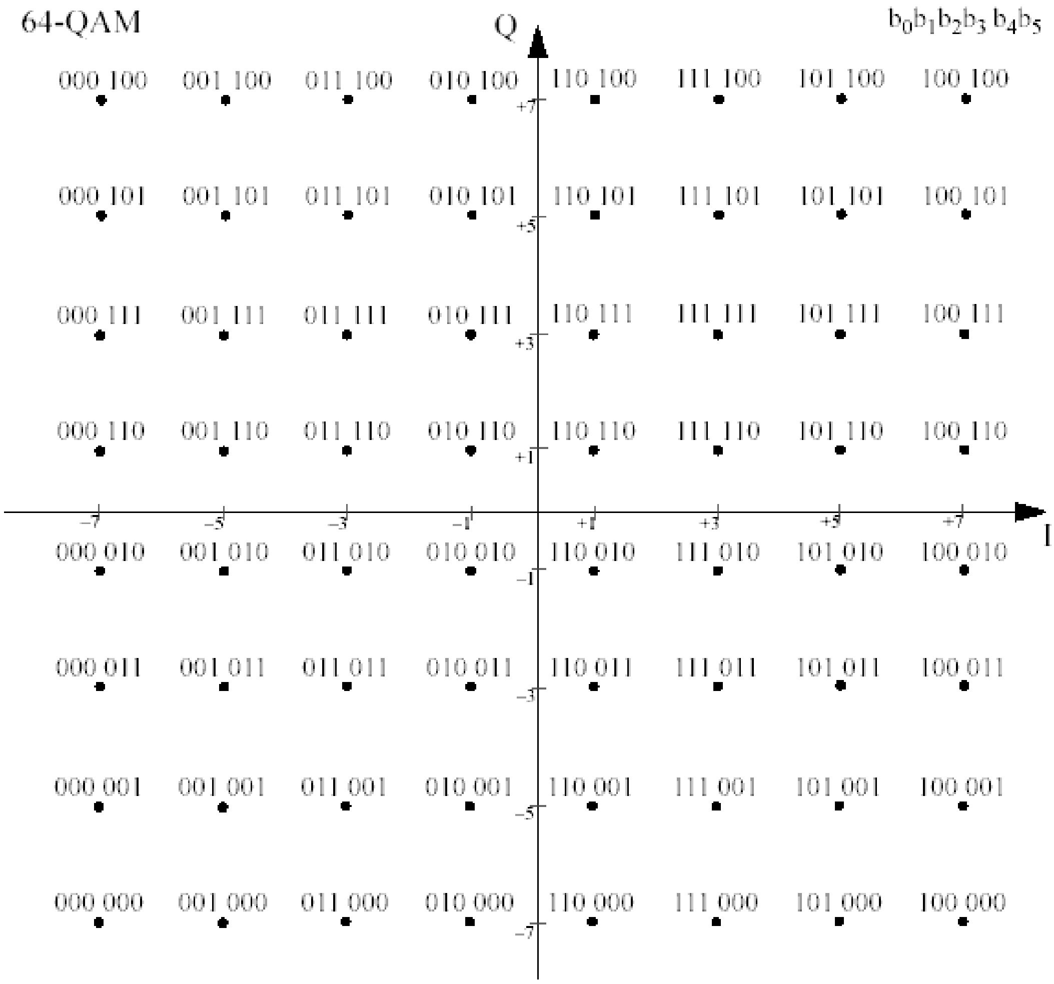

Figure 4.2.1.B – 64 QAM Gray Code

4.2.2 OFDM

Now that the symbols of the transmission are defined the next step is the distribution of each symbol in a different frequency carrier. The OFDM symbol is a group of carriers, each one carrying one modulated symbol. This simulation will be a low-pass equivalent, the carries will not be place in the spectrum at a central frequency, and it only simulates the subcarriers of the channel.

Within the carriers of the OFDM symbol there are some guard carriers witch do not have data symbols. Usually the middle carriers are the ones who send the information. This simulation in particular have 1024 [*N*] OFDM carriers and only 600 [*usedN*] data carriers or 2048 with 1200 data carriers but these two parameters are configurable in the source code.

To create the OFDM signal the data have to be divided in *usedN* length groups creating a [usedN x nOFDMsymbols] matrix. Each one of the group will create a spectrum leaving the guard carriers with zeroes and the data carriers with the complex number of the QAM symbol. Using the Inverse Fast Fourier Transformation we obtain the time signal.

Once the signal is in the time domain these kind of system add a protection or help to the synchronism of the signal. The standard OFDM inserts at the beginning of the signal the last samples of the symbol, this is called Cyclic Prefix (CP). The mission of this redundant information is to reduce the effect of the InterSymbol Interference (ISI) in the multi-path channels.

4.2.3 System diagram

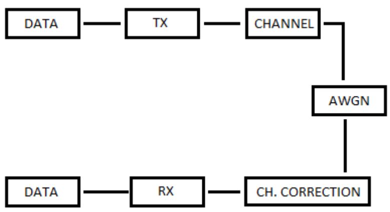

Figure 4.2.3.A – Diagram OFDM

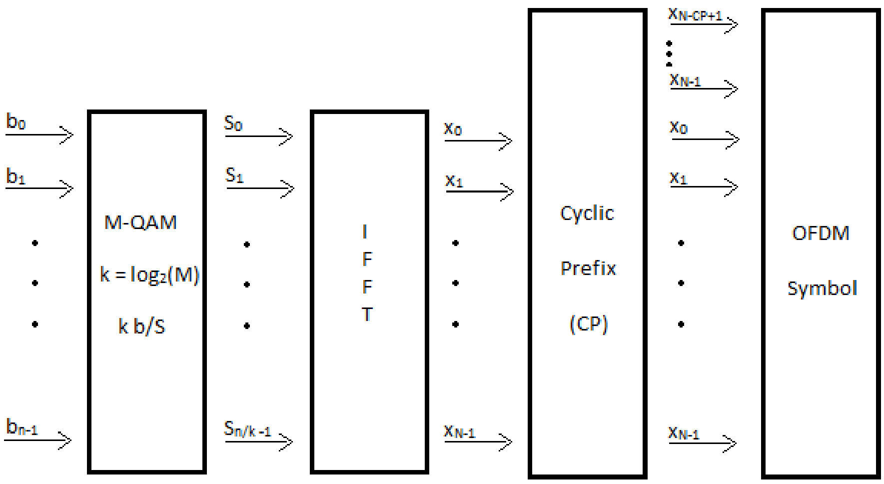

Figure 4.2.3.B – Transmission diagram OFDM

4.2.4 Graphic Example

[Data In]

0	1	1	1	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1	0	1	0

[Symbols In] – 64QAM

28	22	60	8	58

[Data Modulated In]

7 + 3j	1 + 1j	7 – 3j	-7 + 5j	-1 -3j

[Carriers OFDM] – *N* = 1024; *usedN* = 600

N Symbols QAM	*N* Symbols QAM	*N* Symbols QAM

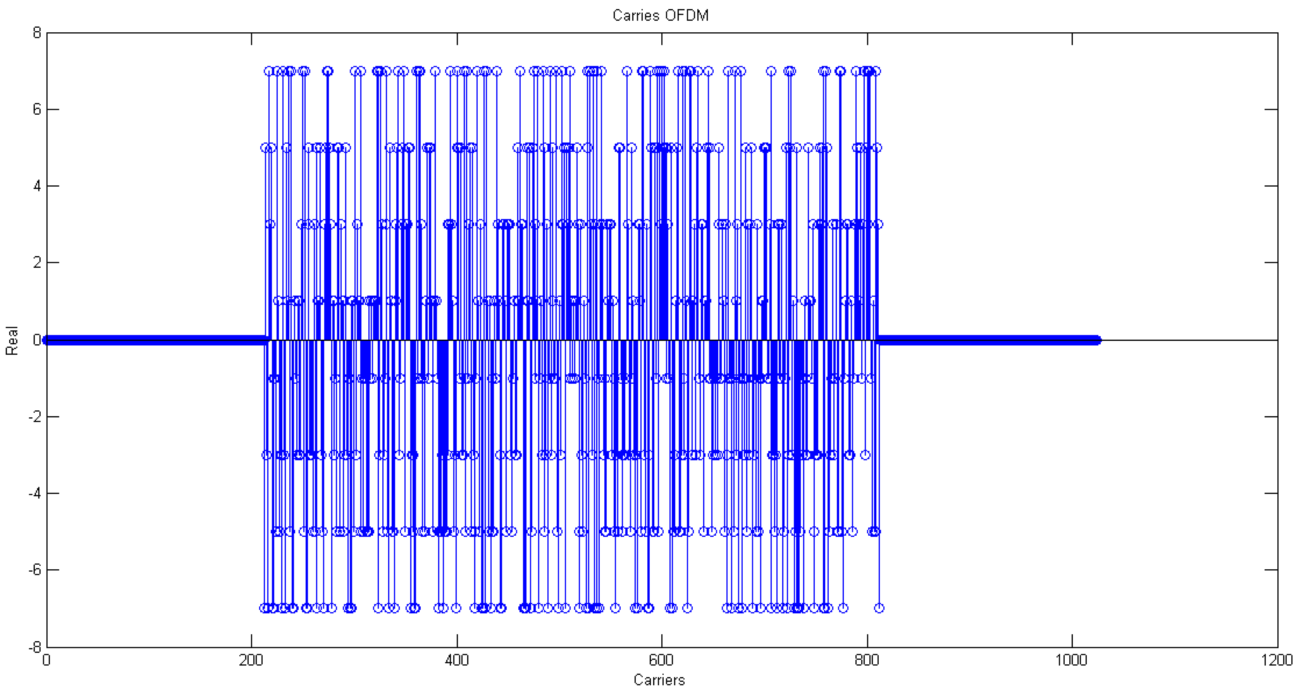

Figure 4.2.4.A – Carriers (real part) OFDM

[Symbol OFDM] – Inverse Fast Fourier Transformation, N time samples

[Ifft] N	[Ifft] N	[Ifft] N

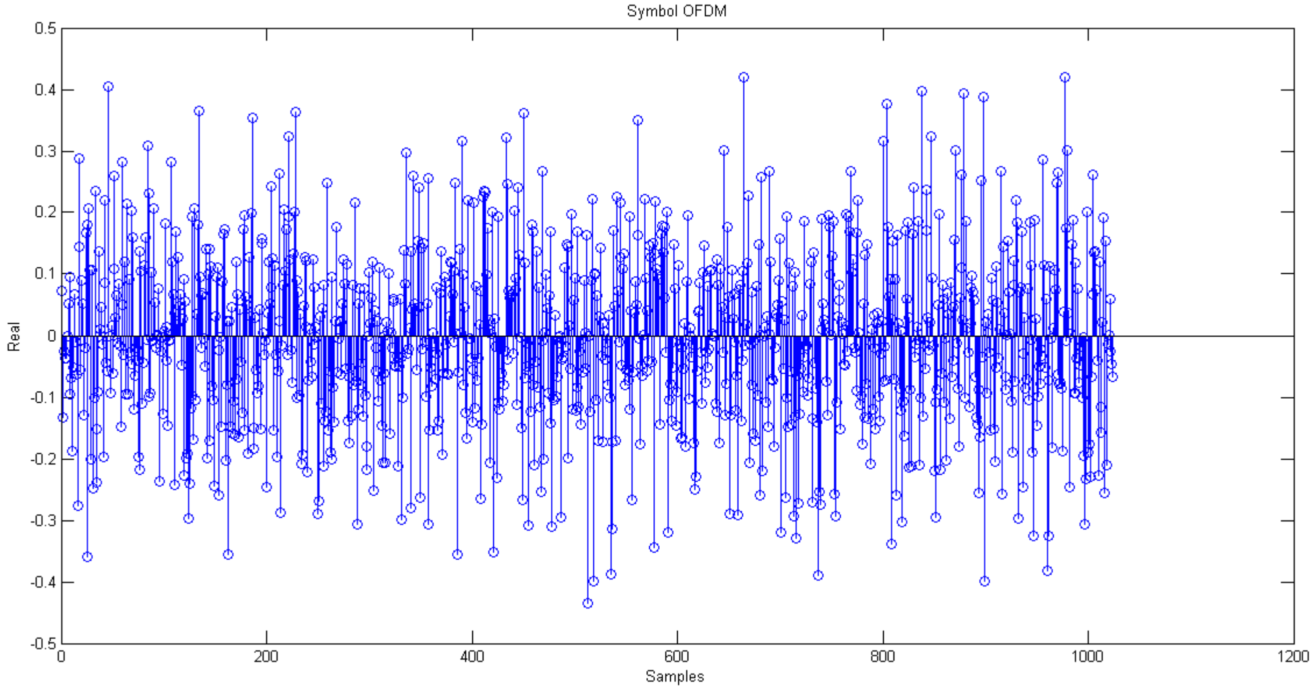

Figure 4.2.4.B OFDM signal (real part) no Cyclic Prefix

[Symbol OFDM + Cyclic Prefix]

CP	N	CP	N	CP	N

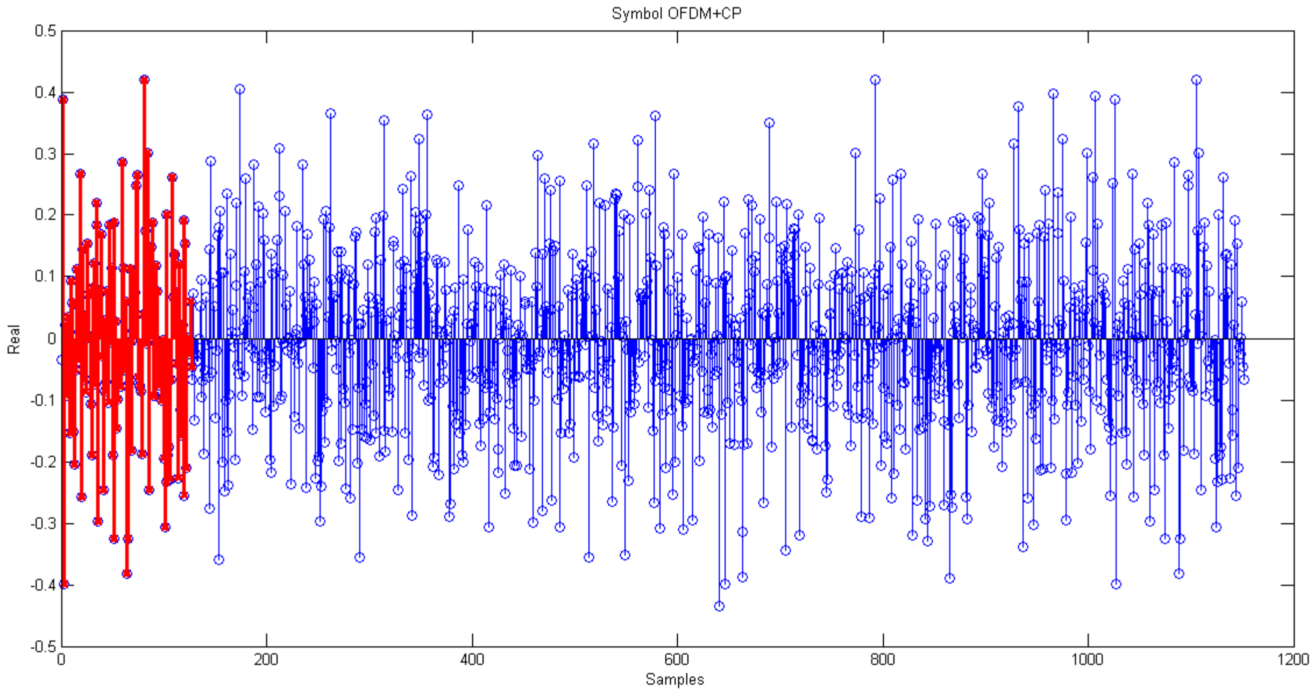

Figure 4.2.4.C – OFDM signal (real part) with Cyclic Prefix

4.3 Reception

At the other end of the communication system we get a sequence of OFDM symbols. This symbols would have been affected by the channel conditions and will require estimation methods to figure the correct modulated symbols out.

Trying to avoid the effect of the multi-path channel the transmission sends a test signal through the channel. The result of this transmission can be interpreted as the effect of the multi-path channel, if that the Signal Noise Ratio of the channel is acceptable. This correction is applied to the carriers of the OFDM symbols, before the Fast Fourier Transformation.

The rest of the system follows the same steps of the transmission, obviously backwards. First of all the Cyclic Prefix is ignored, then it obtains the values of the carriers of each OFDM symbol and extract the QAM symbol after applying the channel correction to the carriers of that symbol.

The QAM symbols that result of the interpretation of the OFDM symbols are estimated by the criteria of nearest symbol of the constellation. This leads to errors due to de Additive White Gaussian Noise and the multi-path effect of the channel. Comparing the final output with the input we can obtain a measure of Bit Error Rate of the transmission.

4.3.1 System diagram

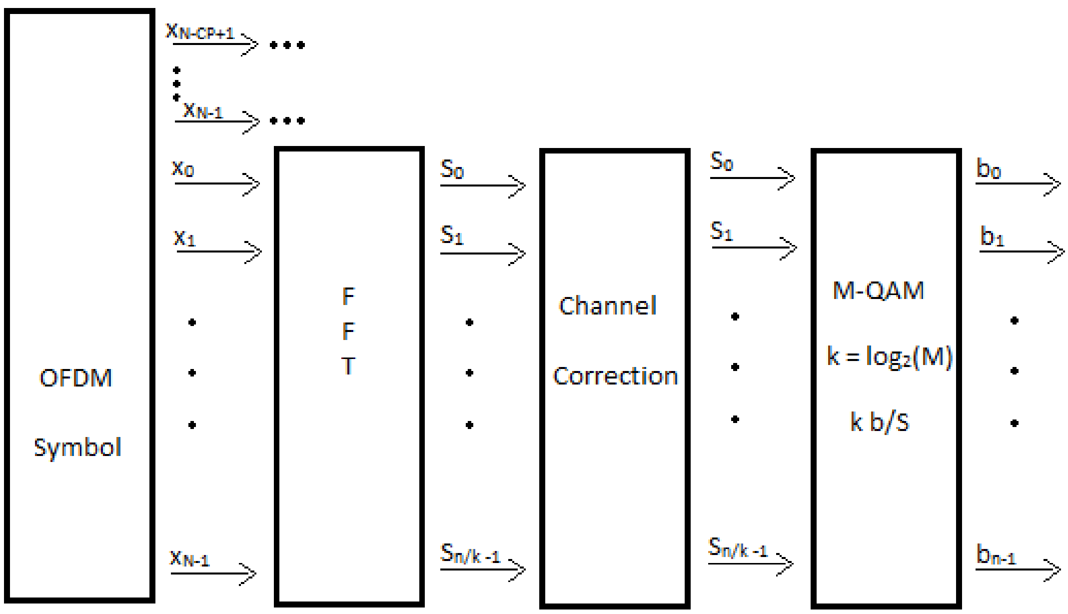

Figure 4.3.1.A – Reception diagram OFDM

4.3.2 Graphic example

[Symbol OFDM + Cyclic Prefix]

CP	N	CP	N	CP	N

[Symbol OFDM]

N	N	N

[Carriers OFDM] – Fast Fourier Transformation

[fft] N Carriers	[fft] N Carriers	[fft] N Carriers

[Channel Correction]

[fft] N Carriers	[fft] N Carriers	[fft] N Carriers
x	x	x
Channel Correction	Channel Correction	Channel Correction

[Data Modulated Rx]

7.2045 + 3.1542j	1.3776 + 1.0087j	7.2231 – 3.0221j	-7.2998 + 5.4378j	-1.0911 -3.8312j

[Data Rx]

0	1	1	1	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1	0	1	0

5 Channel

5.1 Description

With every digital communications system we have to account the physical aspect of it. In this case we are going to be simulating the conditions over a radio frequency air transmission. The transmission is going to be send by multiples transmitters resulting in a sequence of samples of the whole signal with different delay and power.

The other part of the physical channel is the thermal noise of the electronic circuits. All the equipment necessary to process the analog signals produce this noise and modify the siganl. In our case, this effect will be simulated by an Additive White Gaussian Noise channel right before reception step.

5.2 Multi-path channel

Once the signal for the transmission is build, comes into the equation the channel of the communication system. The simulation of the different path of the signal could be easily solved by introducing a filter right before the signal is generated. This filter is built introducing the delays and the power of the different transmissions of the reception perspective.

In this simulation we are going to use the mobile communications channel models, in particular the Long Term Evolution (LTE 4G) channels [2]. These kind of channel would be close to the models that will be use in the next generation systems (5G).

5.2.1 LTE Channel Models

Extended Pedestrian A model (EPA)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	0.0
2	30	-1.0
3	70	-2.0
4	90	-3.0
5	110	-8.0
6	190	-17.2
7	410	-20.8

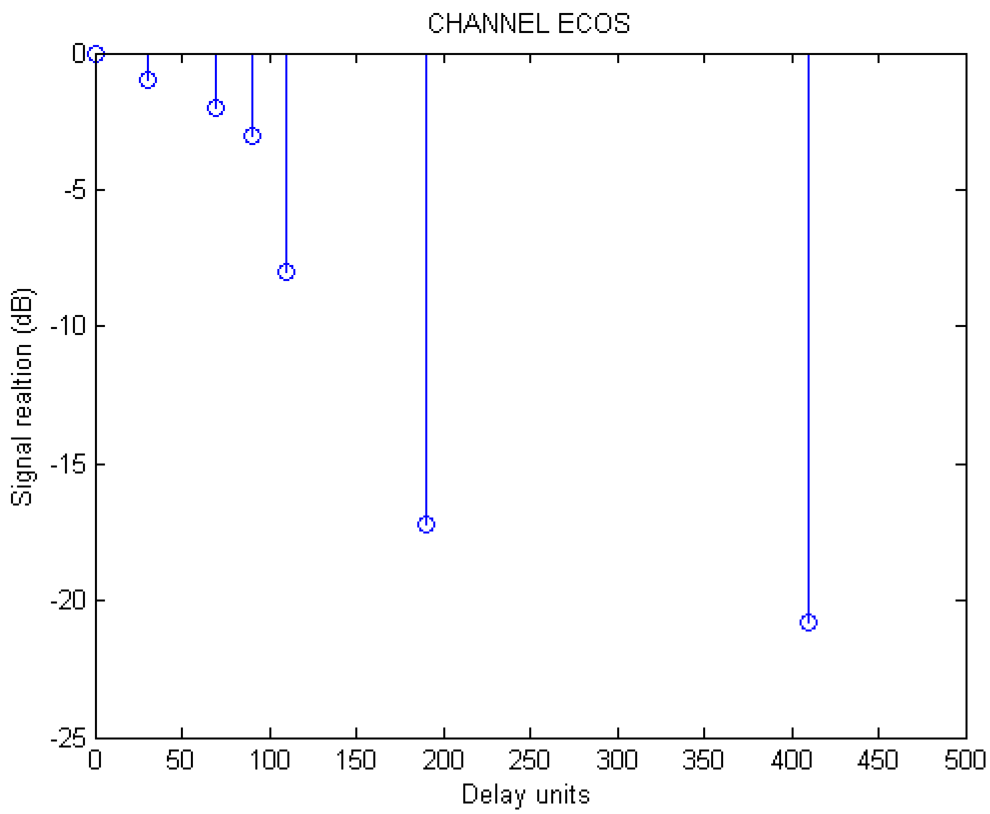

Figure 5.2.1.A – EPA channel model

Extended Vehicular A model (EVA)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	0.0
2	30	-1.5
3	150	-1.4
4	310	-3.6
5	370	-0.6
6	710	-9.1
7	1090	-7.0
8	1730	-12.0
9	2510	-16.9

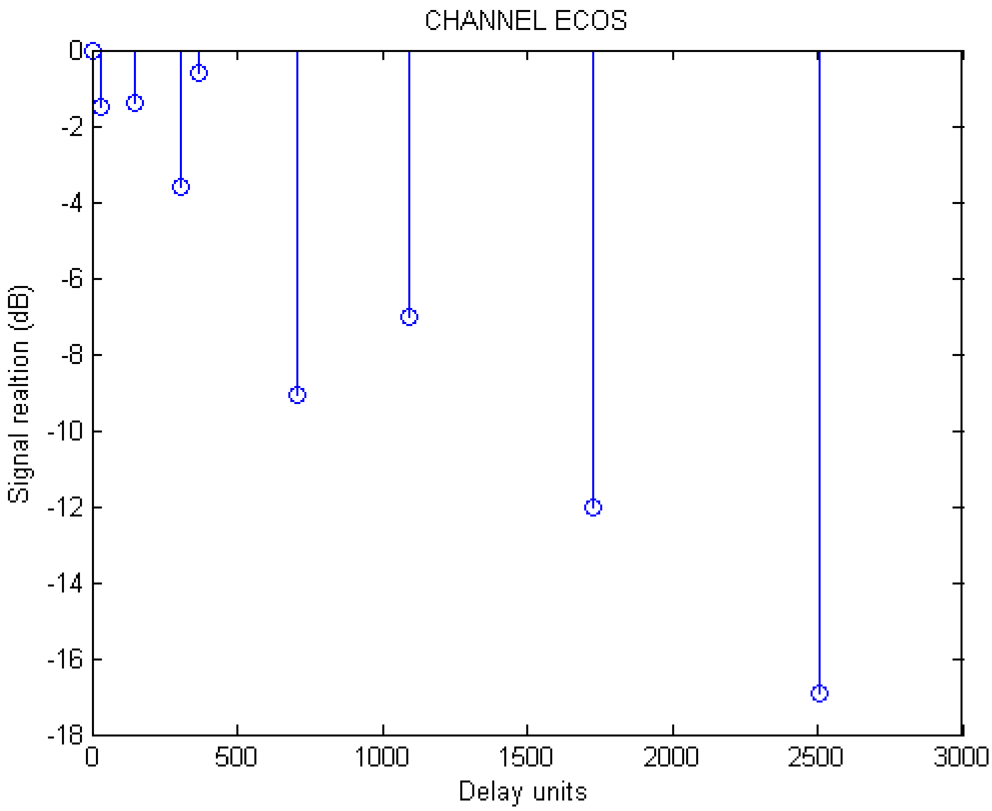

Figure 5.2.1.B – EVA channel model

Extended Typical Urban model (ETU)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	-1.0
2	50	-1.0
3	120	-1.0
4	200	-0.0
5	230	-0.0
6	500	-0.0
7	1600	-3.0
8	2300	-5.0
9	5000	-7.0

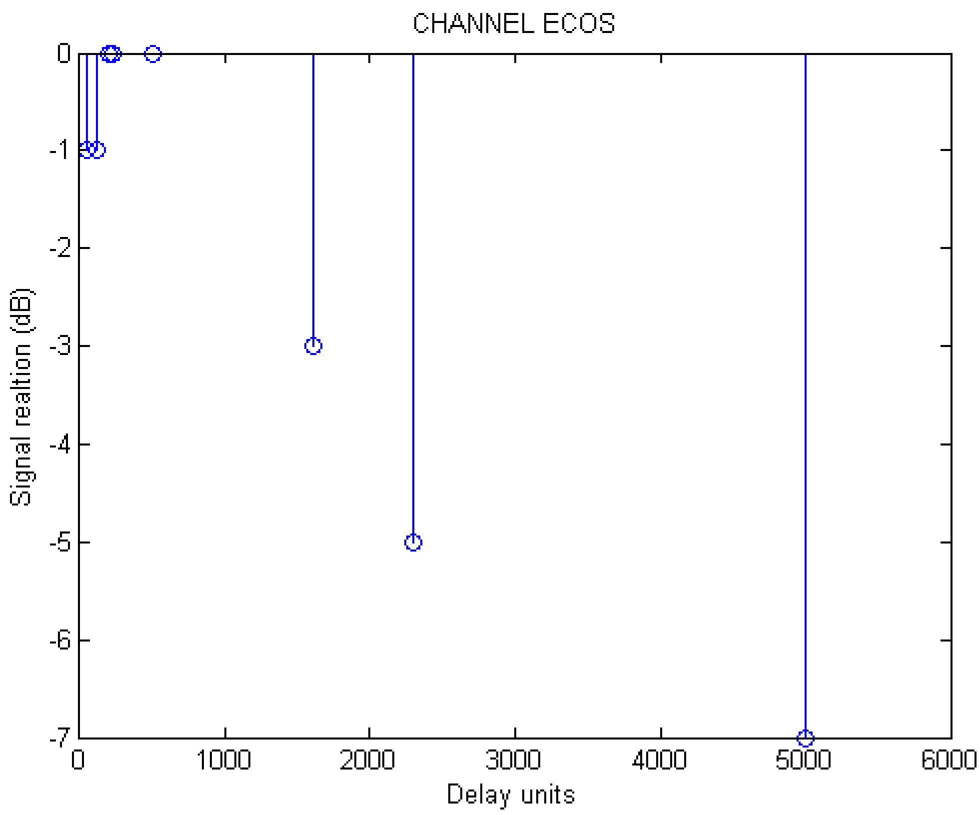

Figure 5.2.1.C – ETU channel model

5.3 Channel estimation and correction

The effect of the multi-path channel has to be treated more carefully than the simple noise addition of the AWGN channel. First the system has to be prepared to analyze the channel in front of it to be able to equalize the received signal.

To estimate the channel both ends of the system have to be synchronized. The transmitter sends symbols different from the QAM constellation and the receiver knows when these test symbols are going to be transmitted. This method allows the receiver to calculate the symbol correction needed to reach the test symbol.

In this simulation the channel estimation is made before sending the useful data, assuming that the channel does not change during the n OFDM symbols of the transmission.

$X(f) = dataModN$ Test symbols of the N carriers of each OFDM symbol.

$Y(f) = dataModNRx$ Test symbols received, N carriers of each OFDM symbol.

$Y(f) = X(f)H(f) = H(f)$ If the test symbols are ones → Channel response.

$$H(f)^{-1} = \frac{1}{H(f)} = \frac{X(f)}{Y(f)} = \frac{1}{Y(f)}$$

Using a transmission of modulated ones the system receive exactly the channel response.

$$H(f)^{-1} = \frac{X(f)}{Y(f)}$$

$Z(f) = dataModNRxFixed$ Corrected test symbols of the N carriers of each OFDM symbol.

$$Z(f) = X(f)H(f)H(f)^{-1} = Y(f)H(f)^{-1}$$

The received signal is affected by the AWGN channel as well as the multi-path channel. In the simulation the estimation is performed in the same conditions as the data transmission. This can cause errors in the estimation and therefore in the correction.

5.4 Bandwidth

Throughout the simulation the data is calculated as discrete samples. To adapt this samples to the multi-path channel models it needs the reference of the bandwidth of the transmission. Establishing the frequency of the samples they can be interpreted in time domain. In this simulation in particular, the transmission is simulating LTE communications and their maximum bandwidth is 20 MHz.

$$BW = 20\ MHz \rightarrow t_{sample} = {}^{1}/_{BW} = 50\ ns$$

The adaptation of the multi-path channel models has to consider t_s to place the taps in the correct samples:

$$t_{tap}/t_{sample} = echo\ sample$$

This operation usually is not an integer number so it is going to affect to the next sample. In other words, if the tap is at 150 ns the echo is going to be in the fourth sample of the channel. Some of the channel models have the problem of having a tap in less than t_s, this means that the echo would affect the main signal. This has been resolved in the simulation by delaying the first tap so it affects the second sample of the channel (being the main signal the first). For example:

Extended Vehicular A model (EVA)

Tap	Excess tap delay [ns]	Relative power [dB]
1	0	0.0
2	50	-1.5
3	150	-1.4
4	310	-3.6
5	370	-0.6
6	710	-9.1
7	1090	-7.0
8	1730	-12.0
9	2510	-16.9

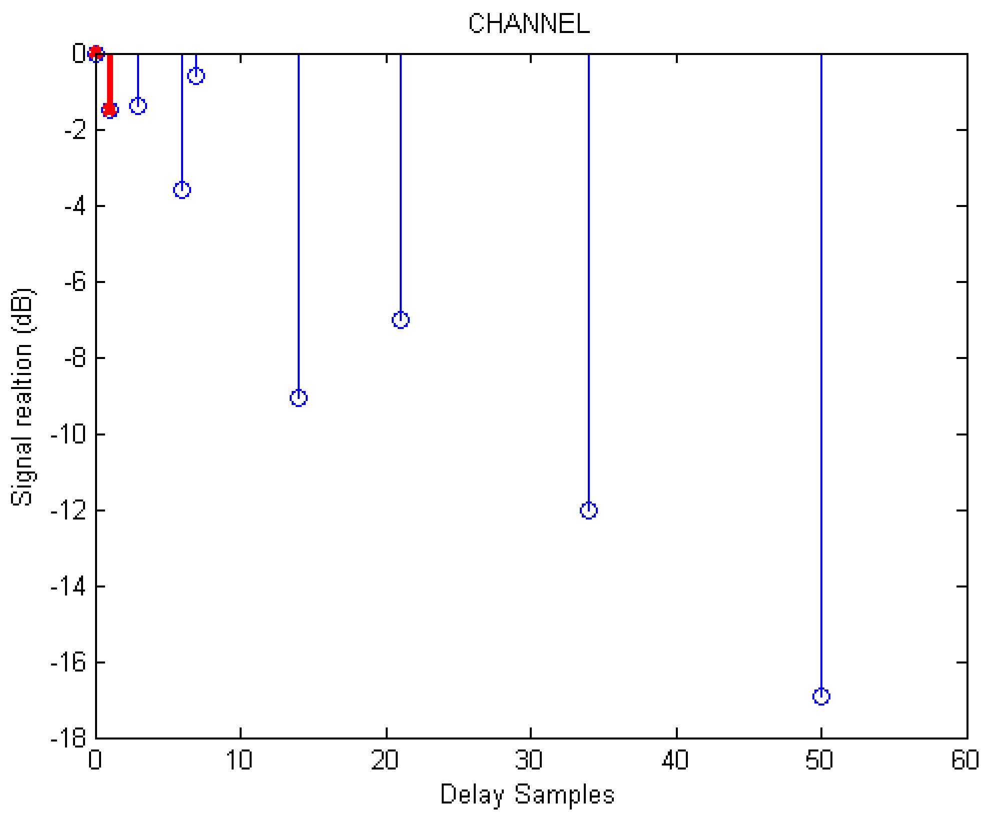

Figure 5.4.A – EVA channel model modified

5.5 Additive White Gaussian Noise channel

Once the signal pass through the multi-path channel it only needs the noise effect to simulate the analog signal that is going into the reception systems. This noise is simply a degradation determined by the addition of a normal distribution with zero mean and N_0 standard deviation.

The noise power is defined by the standard deviation of this function. The relation of the noise power and the signal power is called Signal Noise Ratio (SNR) and in digital communications is usually replaced by E_bN_0 witch establish the relation with the bit energy and the noise of the system.

In this particular case, the signal power also depends on the guard carriers of the spectrum and the length of the Cyclic Prefix.

$$SNR = \frac{N}{(N + CP)} * \frac{usedN}{N} * k * EbN0$$

N = total number of carriers OFDM = ifft samples;

usedN = data carriers OFDM;

k = bits / symbol QAM;

EbN0 = bit energy to noise ratio;

To validate this simulation we can compare the system Bit Error Rate (BER) and the E_bN_0 of the signal with the theoretical results based in error probability with the normal distribution in each constellation of QAM symbols. The equation for different M-QAM systems is as follows:

$$P_{Symb\ Error} = 2. erfc\ (\sqrt{3\ k \frac{EbN0}{2\ (M-1)}})$$

$$P_{Bit\ Error} = \ P_{Symb\ Error}\ .k$$

erfc() = complementary error function;

M = number of QAM symbols;

The complex noise signal needed is calculated as follows:

$$S = Var(ofdm\ signal)$$

$$Var(N0) = \frac{S}{SNR}$$

$$Var(Q) = Var(I) = {}^{Var(N0)}/_{2}$$

$$Std\ (Q) = Std(I) = \ \sqrt{Var(Q)} = \ \sqrt{Var(I)}$$

$$Noise_Q = Noise_I = N\big(0, Std(Q)\big)$$

S = signal power;

SNR = signal to noise ratio;

I = real part of the symbol;

Q = imaginary part of the symbol;

The effect of this cannel is shown in the constellation diagram witch is the visual method to fully understand what is happening in the whole system. The black points mark the position of the original symbols and the green represents their deviation at the reception point.

E_bN_0 = 15 E_bN_0 = 20 E_bN_0 = 30

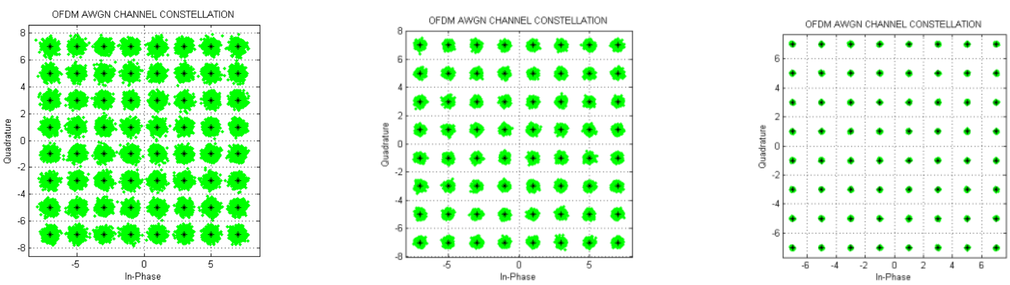

Figure 5.5.A – Channel AWGN constellations

The deviation can cause errors in the received symbols. By using Gray coded modulation this error has to be large to cause more than a one bit error in that symbol. Comparing the error results given in simulations with different E_bN_0 it can be shown that the system works very close to the theoretical calculations.

6 OFDM Zero Tail

6.1 Description

The OFDM model is completely defined now it can be the reference to experimental system changes. The use of the Cyclic Prefix have been a redundant way to solve synchronization problems since the beginnings of these kind of communication systems. The transmission of redundant data is always a power waste and a bandwidth misuse.

Using this train of thought we are going to make some changes to the model removing the Cyclic Prefix and adding a tail of zeroes instead. The system follow the same diagrams and pass through the same channels as before, the significant changes are in the transmission and the reception.

6.2 Transmission

The OFDM signal in this case is created by the same steps as the previous system. The difference between them is in the time domain processing of the OFDM symbols. Now this symbols, instead of having a redundant header, have a tail of zeros (ZT) at the end.

6.2.1 System diagram

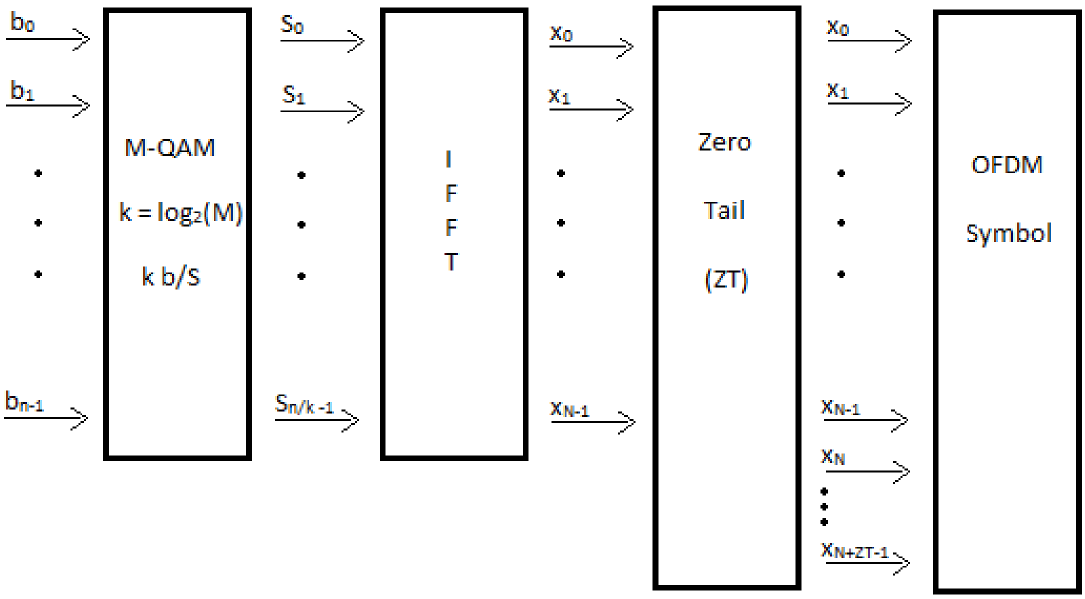

Figure 6.2.1.A – Transmission diagram OFDM ZT

6.2.2 Graphic example

[Data In]

0	1	1	1	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1	0	1	0

[Symbols In] – 64QAM

28	22	60	8	58

[Data Modulated In]

7 + 3j	1 + 1j	7 – 3j	-7 + 5j	-1 -3j

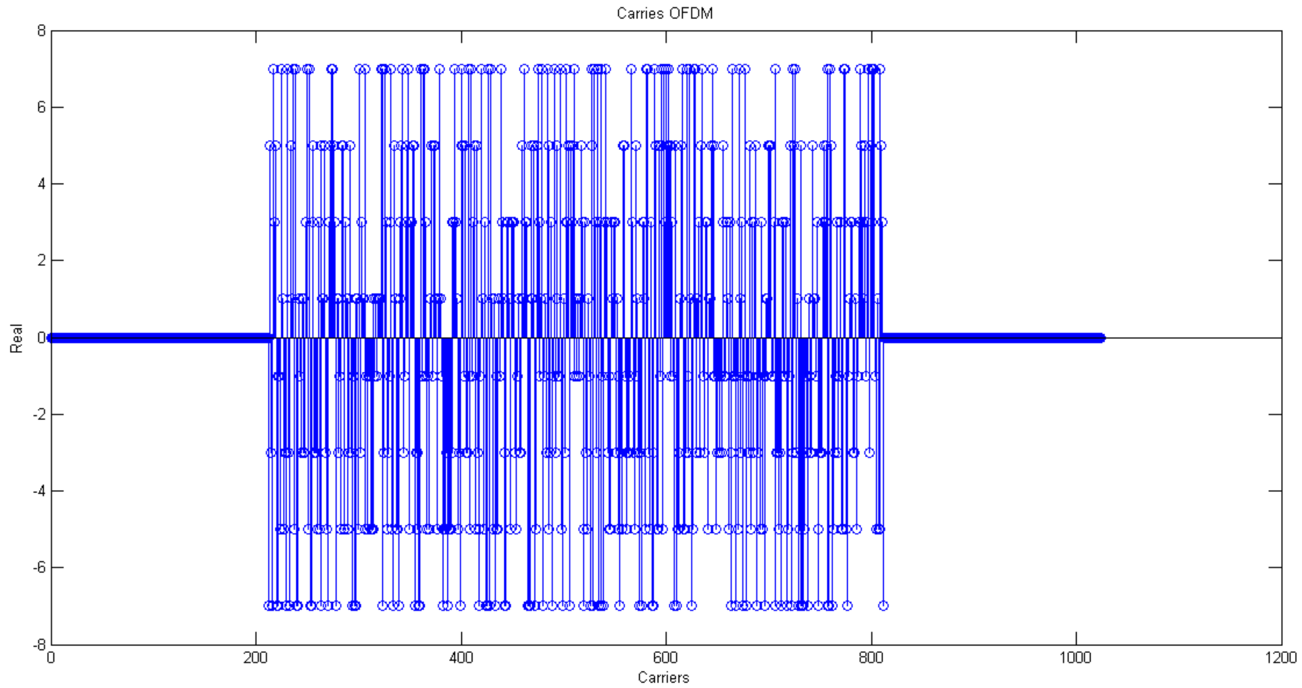

Figure 6.2.2.A – Carriers (real part) OFDM

[Carriers OFDM] – *N* = 1024; ***usedN*** = 600

N Symbols QAM	*N* Symbols QAM	*N* Symbols QAM

[Symbol OFDM] – Inverse Fast Fourier Transformation, N time samples

[Ifft] N	[Ifft] N	[Ifft] N

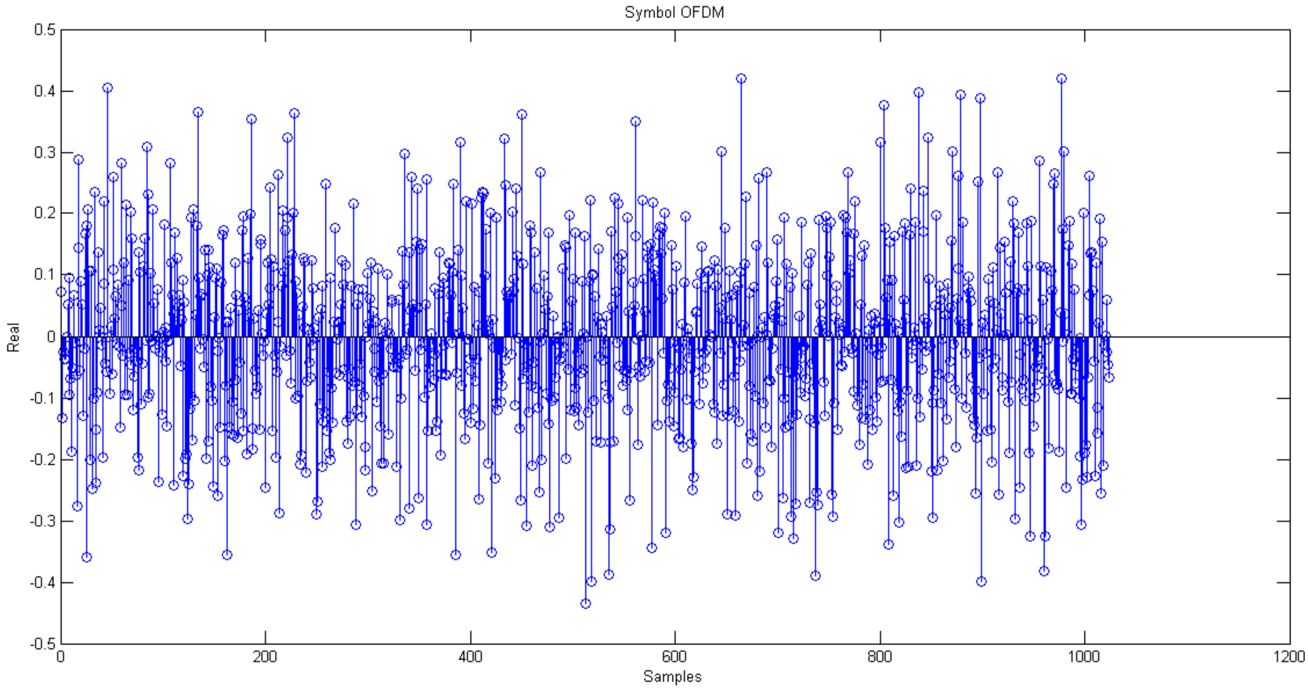

Figure 6.2.2.B – OFDM signal (real part)

[Symbol OFDM + Zero Tail]

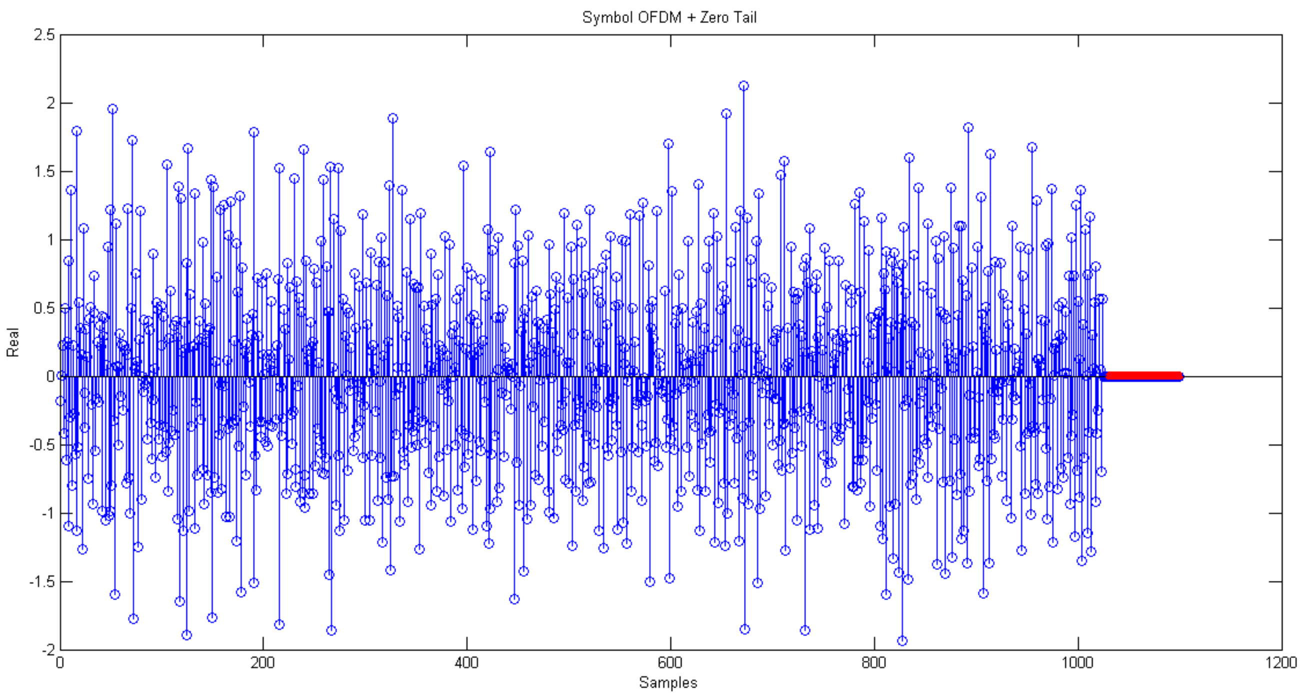

Figure 6.2.2.C – OFDM signal with Zero Tail (real part)

6.3 Reception

When this new kind of OFDM symbol pass through the multi-path channel, the convolution is affected by the non-cyclical aspect of the new signal. The reception cannot be done only looking at the N time samples of the received symbol because the tail of zeroes carries information about the convolution results; in the previous case this information was redundant. To take into consideration this Zero Tail information the value of the samples of it are added to the first symbol samples [3]. This method is called Overlap-and-add block convolution and allow us to recover the N samples of the new OFDM symbol and use them the same way as the previous system but eliminates the advantage of discarding the extra samples.

6.3.1 System diagram

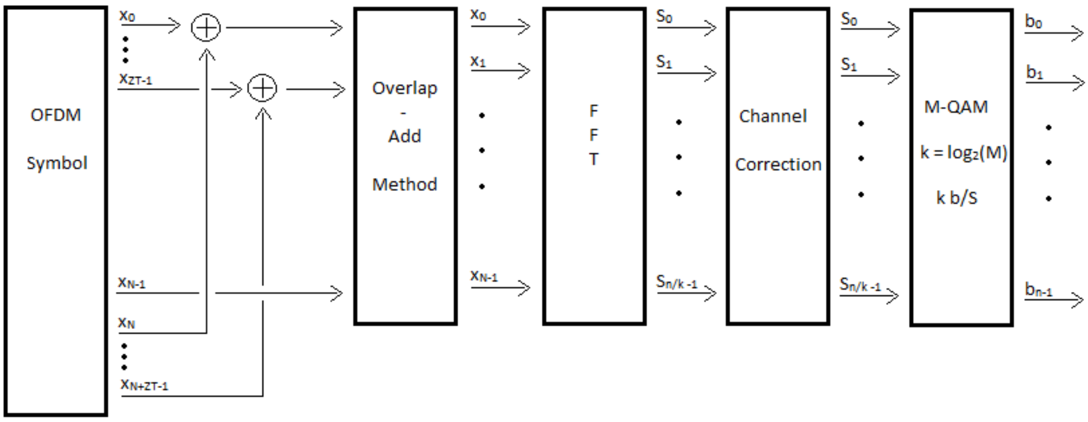

Figure 6.3.1.A – Reception diagram OFDM ZT

6.3.2 Graphic example

[Symbol OFDM + Zero Tail]

N	ZT	N	ZT	N	ZT

[Symbol OFDM]

N (overlap-and-add)	N (overlap-and-add)	N (overlap-and-add)

[Carriers OFDM] – Fast Fourier Transformation

[fft] N Carriers	[fft] N Carriers	[fft] N Carriers

[Channel Correction]

[fft] N Carriers	[fft] N Carriers	[fft] N Carriers
x	x	x
Channel Correction	Channel Correction	Channel Correction

[Data Modulated Rx]

7.2045 + 3.1542j	1.3776 + 1.0087j	7.2231 – 3.0221j	-7.2998 + 5.4378j	-1.0911 -3.8312j

[Data Rx]

0	1	1	1	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0	0	1	1	1	0	1	0

6.4 Channel estimation and correction

Using the Overlap-and-add block convolution the received signal still has the effect of the multi-path channel the same way as before. The effect of this echoes can be compensated using a parallel method to the previous OFDM. Sending a test signal through the channel using the new transmission system (inserting the Zero Tail) we can estimate the correction needed. Of course the reception of this test signal has to be done with this last reception system to get a useful estimation.

7 OFDM DFT-spread Zero Tail

7.1 Description

This method expands the idea of the trailing zeros in the time domain of the signal. Once the simple Zero Tail model is done and tested the experimentation keeps on going. The new idea of this OFDM system is the use of two IFFT blocks, one of them after adding the Zero Tail. Another new aspect of it is the addition of a short zero header (0_h and 0_t) instead of placing all the zeros at the end of the signal [4].

7.2 Transmission

The main problem about this new signal is the relation of IFFT samples and real data carriers. The first step of the signal is basically the same one of the OFDM Zero Tail. Now the first group of data carriers witch pass through the IFFT block is smaller than *usedN*:

$$\text{ofdmSymbol} = \text{IFFT} (\text{dataMod} , \text{usedN} - \text{ZT})$$

$$\text{ofdmSymbolZT} = [\ 0_h \ \text{ofdmSymbol} \ 0_t]$$

When the time domain zeros are placed, the second IFFT block insert the guard carriers.

$$\text{dataModUsedN} = \text{FFT} (\text{ofdmSymbolZT}, \text{usedN})$$

$$\text{dataModN} = [\ \text{guardCarriers} \ \ \text{dataModUsedN} \ \ \text{guardCarriers}]$$

$$\text{ofdmSymbolDFT} = \text{IFFT} (\text{dataModN} , \text{N})$$

dataMod = QAM symbols;

N = number of OFDM carriers;

usedN = number of non-guard carriers;

0_h = zero header; 0_t = zero tail;

ZT = number of zeros = $0_h + 0_t$;

The input data has to reshape in *usedN-ZT* blocks and because of that there are some of the QAM symbols that have to be discarded in order to adapt the input symbols of the previous models to the new transmission system. Now the input data matrix is [(usedN-ZT) x nOFDMSymbols].

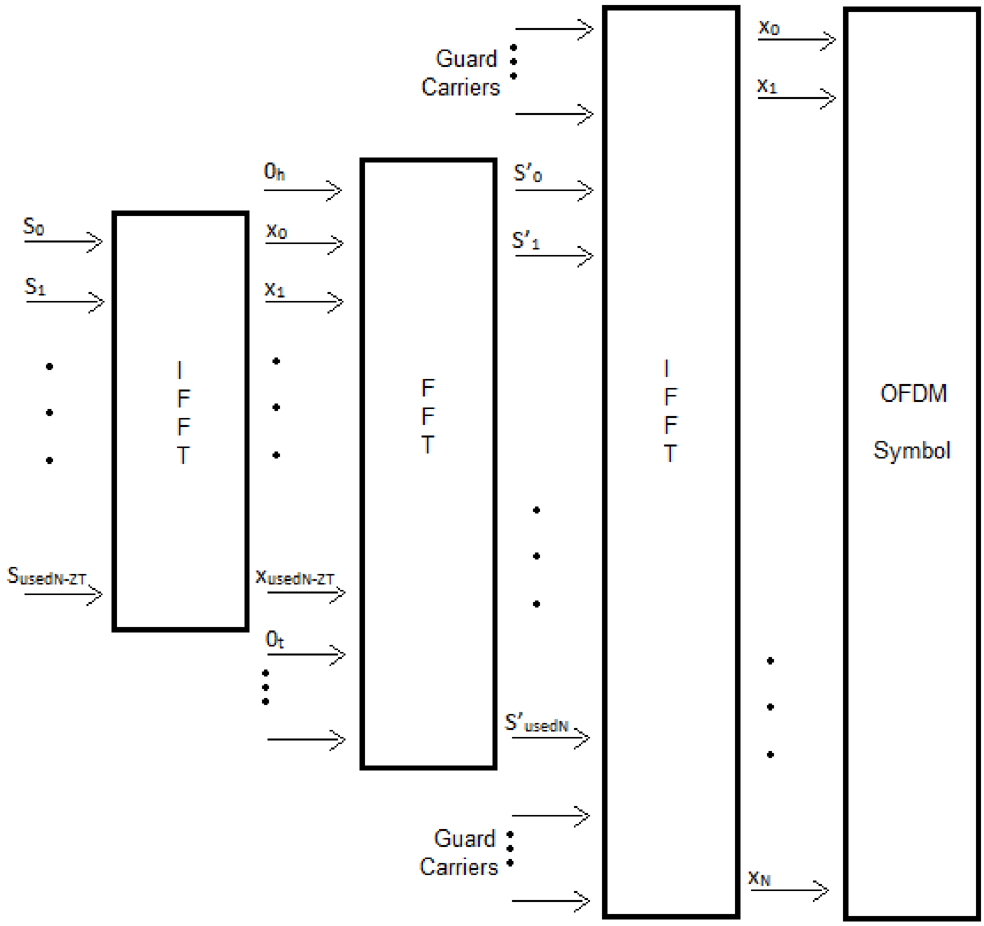

Figure – 7.2.A Transmission Diagram OFDM DFT-s Zero Tail

8 Simulation

8.1 Description

The simulation is based in *MATLAB* code, three main scripts and different functions to perform the system steps. It represents a low-pass equivalent of the OFDM systems implemented. All the functions are named in uppercase and using underscore instead of spaces; the scripts are named in lowercase. Throughout the source code there are comments to guide the process.

8.1.1 Main simulation

This script uses a common input data for all the different systems of the simulation. All these parameters determine the length of the random vector of bits to be sent in all the simulations. This input data has to be carefully set to have a controlled simulation of each system. The test of the code have been made using 64-QAM as the modulation standard and it only could work using square constellations.

Input data:

- M = Number of QAM symbols of the constellation
- Number of carriers
- Number of data carriers
- Number of OFDM symbols to send
- Length of the Cyclic Prefix
- Length of the Zero Tail
- Number of OFDM symbols to estimate the channel
- Bit energy to noise ratio (E_bN_0) [dB]
- Bandwidth [Hz]
- Single-path/Multi-path channel model

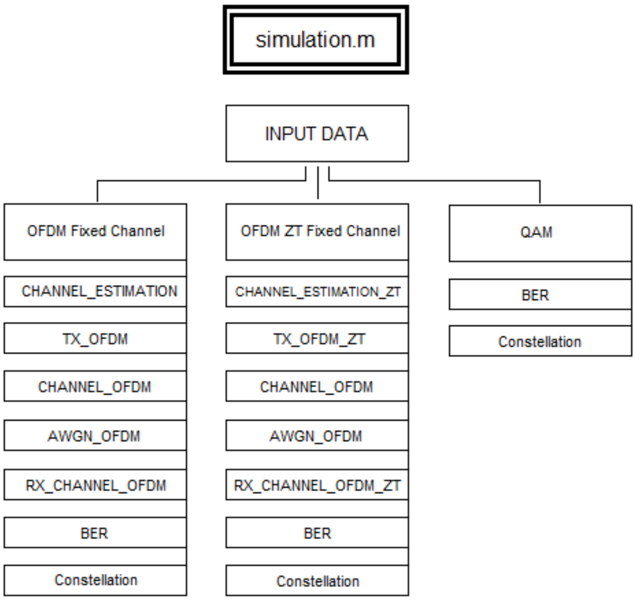

Figure 8.1.1.A – Simulation code scheme

8.1.2 BER vs EbN0 curves simulation

To obtain the Bit Error Ratio curves the simulation has to generate multiple transmissions and their analysis changing the value of E_bN_0. This is done in a new *MATLAB* script witch adds a loop that changes this value right before it obtains the BER value. All of the previous simulation script INPUT DATA values have to be configured. The loop goes through a vector of E_bN_0 values than can be also modified in the INPUT DATA section of this script.

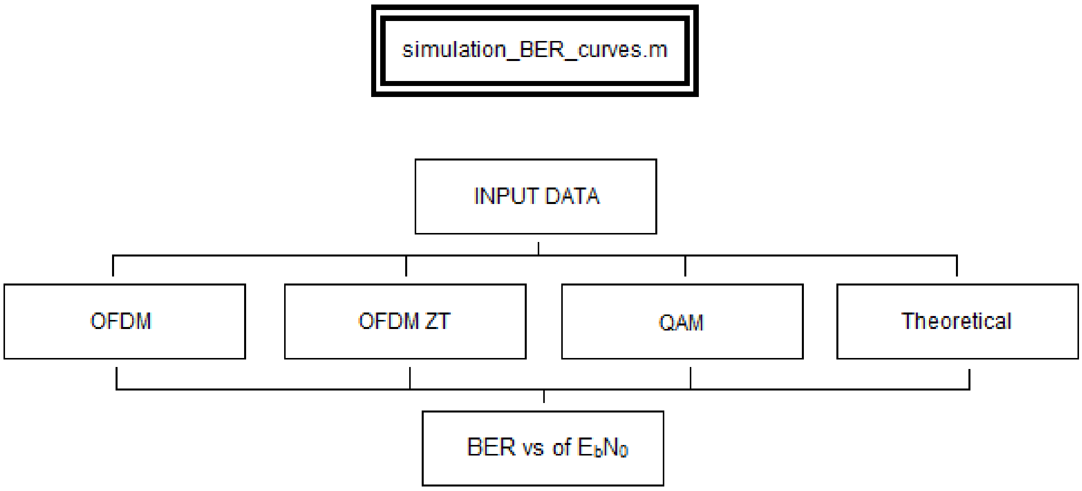

Figure 8.1.2.A – Simulation BER curves scheme

8.1.3 OFDM DFT-spread simulation

This *MATLAB* script compares the three different OFDM signals and their spectrums. Here the data input is the same for the three and the simulation only creates the waveform to be sent through the channel. The DFT-spread waveform is not included in the main simulation because of the lack of reception model.

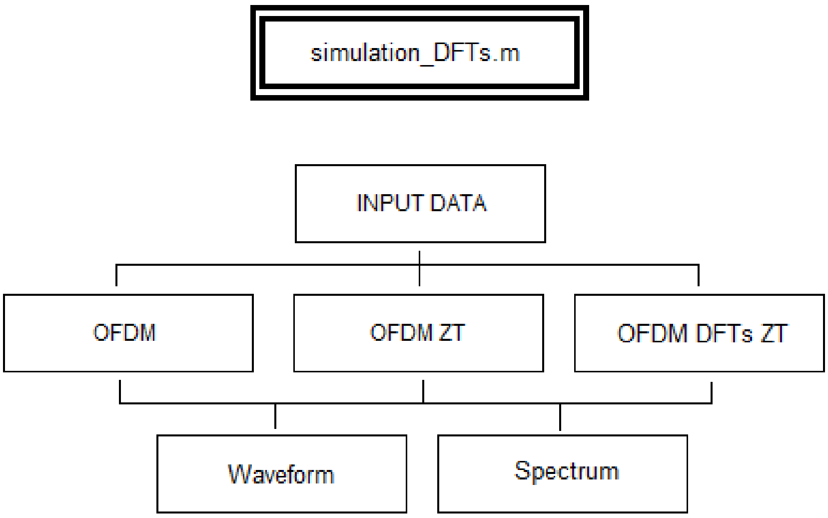

Figure – 8.1.3.A Simulation DFT-spread scheme

8.2 Validation

8.2.1 AWGN channel

The noise addition must be related to the signal power, the measure of this noise is a ratio comparing the signal and the noise power. In the simulation this step is performed using a *MATLAB* function, explained with “>> help awgn”:

Y = awgn(X,SNR) adds white Gaussian noise to X. The SNR is in dB.

The power of X is assumed to be 0 dBW. If X is complex, then

awgn adds complex noise.

% To cause awgn to measure the power of X and add noise to

% produce a SNR of 4, use:

*X = sqrt(2)*sin(0:pi/8:6*pi);*

Y = awgn(X,4,'measured');

Therefore this step is at the end of the transmission system. The noise is added just before the reception step to take into consideration the power of the signal once it has passed through the multi-path channel.

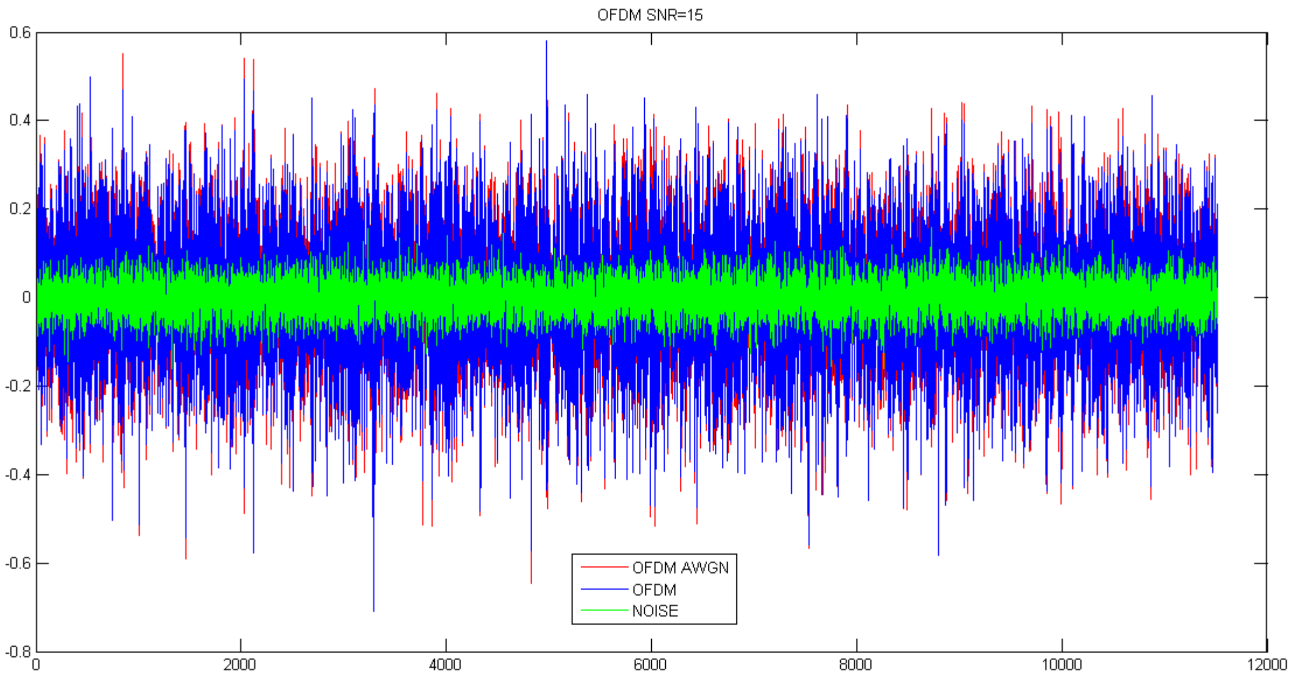

Figure 8.2.1.A – OFDM example AWGN SNR = 15

8.2.2 BER vs E_bN_0

The simulation of the transmission error is done by sending 1000 OFDM symbols through a changing AWGN channel to see the effect with different values of E_bN_0. The first step is creating a simple M-QAM transmission and compare it to the theoretical value of the Bit Error Rate that it's explained in the section 3.5.

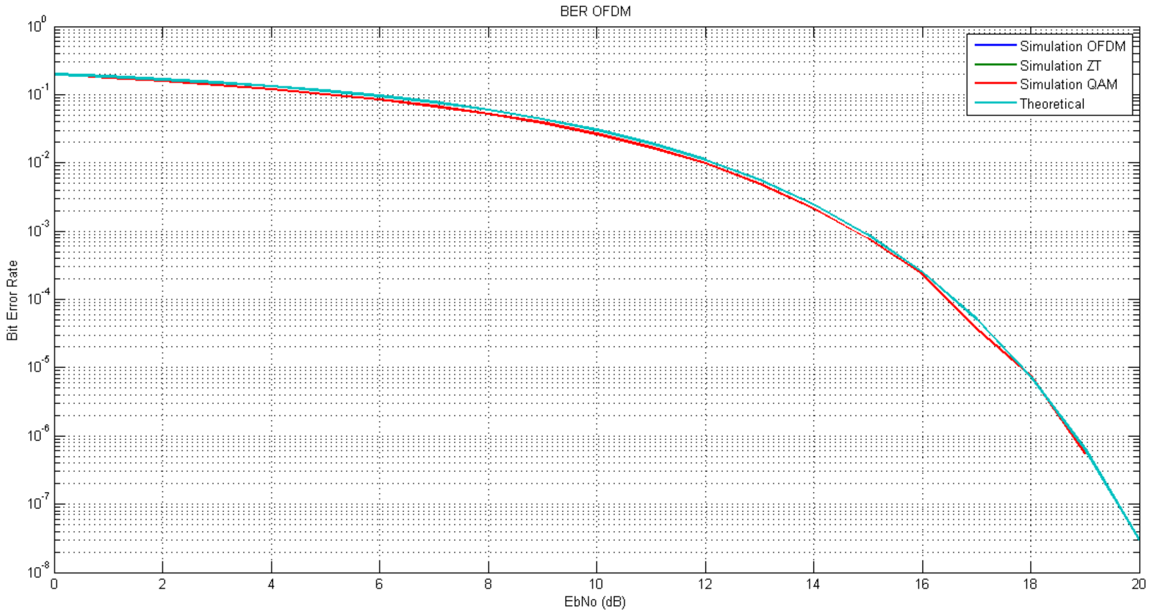

Figure 8.2.2.A – M-QAM BER vs E_bN_0

Once the OFDM transmission is created it has to work with similar BERs when there is no multi-path channel and no correction involve.

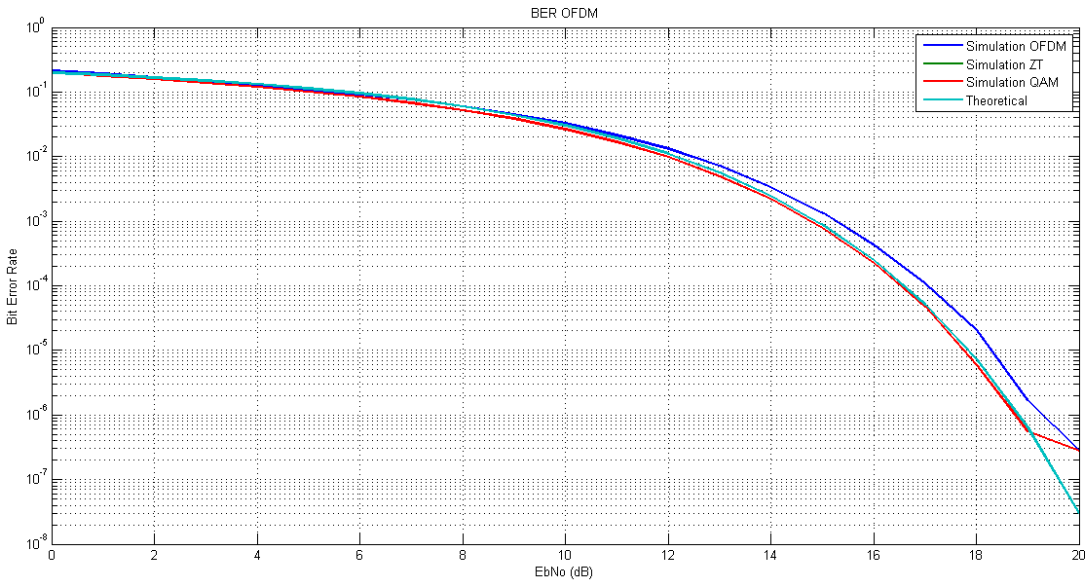

Figure 8.2.2.B – OFDM no multi-path channel BER vs E_bN_0

8.2.3 Channel estimation

The test symbols the system uses to estimate the channel are sent in the same conditions as the useful symbols, using the same multi-path and AWGN channels. The number of test symbols can be configured and the mean of all the symbols response avoid the effect of the channel noise. To validate the estimation we configure the E_bN_0 to a high value to have noise free transmission and see the correction.

The effect of the multi-path channel is compensated in the transmission if the carrier correction is calculated properly. In the next example we use a large value of E_bN_0 and see the results of the carrier correction.

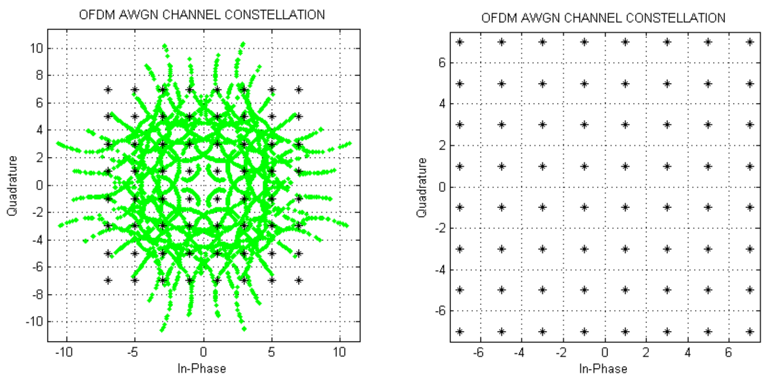

Figure 8.2.3.A – Constellation channel model EPA vs fixed

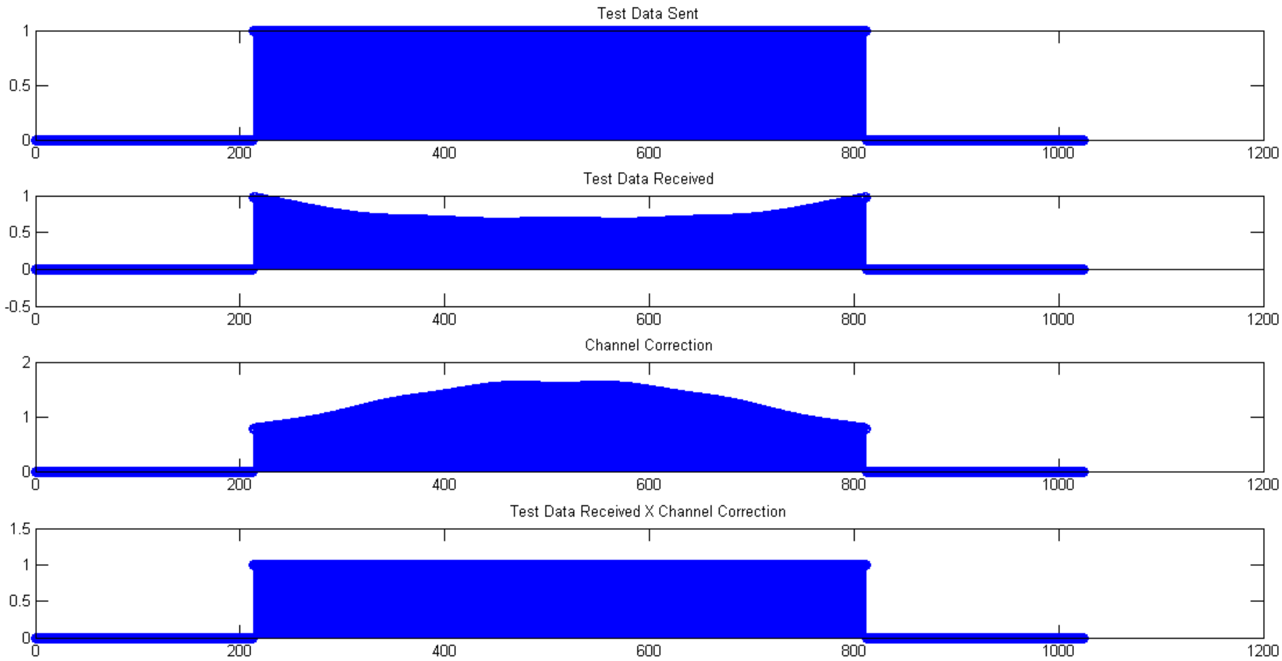

Figure 8.2.3.B – Channel Estimation EPA channel model

8.3 Results

8.3.1 BER vs E_bN_0 without channel estimation

The first step in the simulation is establishing the transmission with a single-path and AWGN channel to validate the different systems and compare their behavior in optimal conditions.

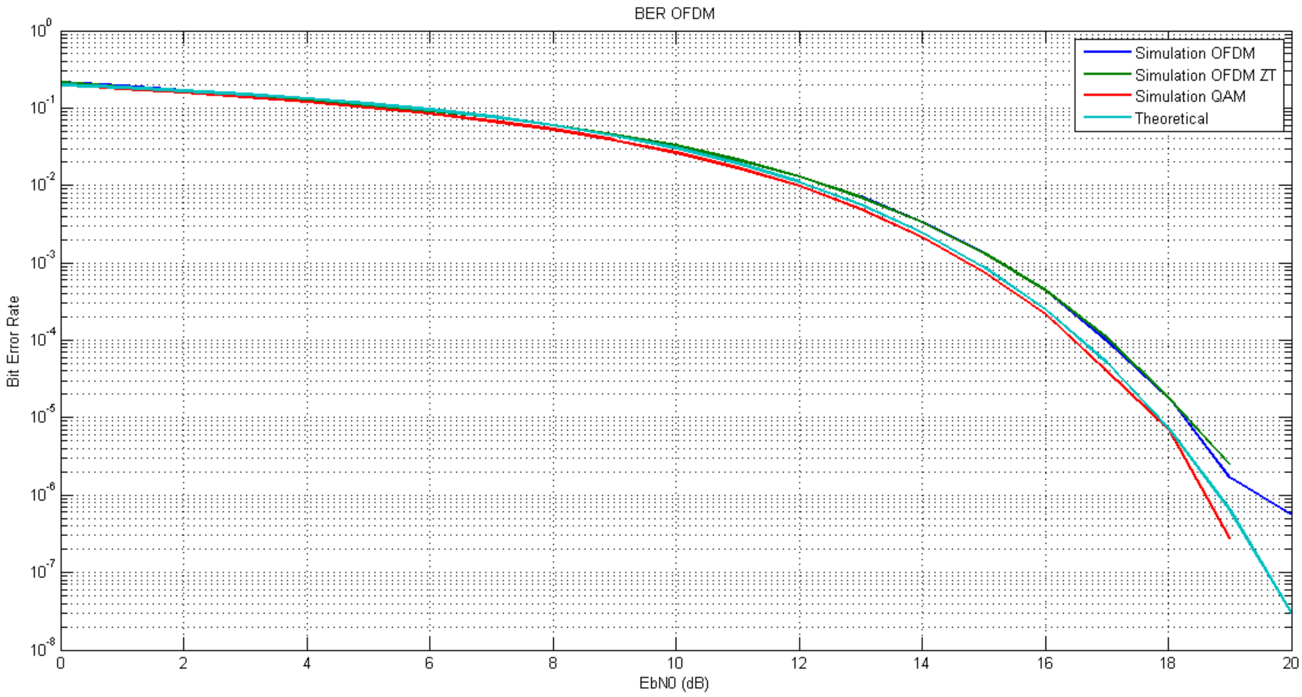

Figure 8.3.1.A – BER vs E_bN_0 no channel estimation

In the figure is shown that the result with the OFDM with Cyclic Prefix and the OFDM with Zero Tail is almost identical in terms of the effect of an AWGN channel. The noise in the transmission has the same impact in the two systems. As long as the systems don't pass through any filter, the noise effect is the same in the two waveforms.

8.3.2 BER vs E_bN_0 using channel estimation

Keeping the single-path channel the simulation estimate the channel and compensate the received carriers. This the channel correction is affected by the deviation attach to the noise and it can cause a compensation error.

This can be solved by sending more test symbols to estimate the channel. Using the mean of the results of all the estimation symbols the simulation can eliminate the random noise from the channel correction and compensate the carriers properly. Using 20 test symbols instead of 2 the simulation shows the improvement.

Finally it can be shown again that in a single-path channel the two systems perform almost identically even with the two different channel estimations.

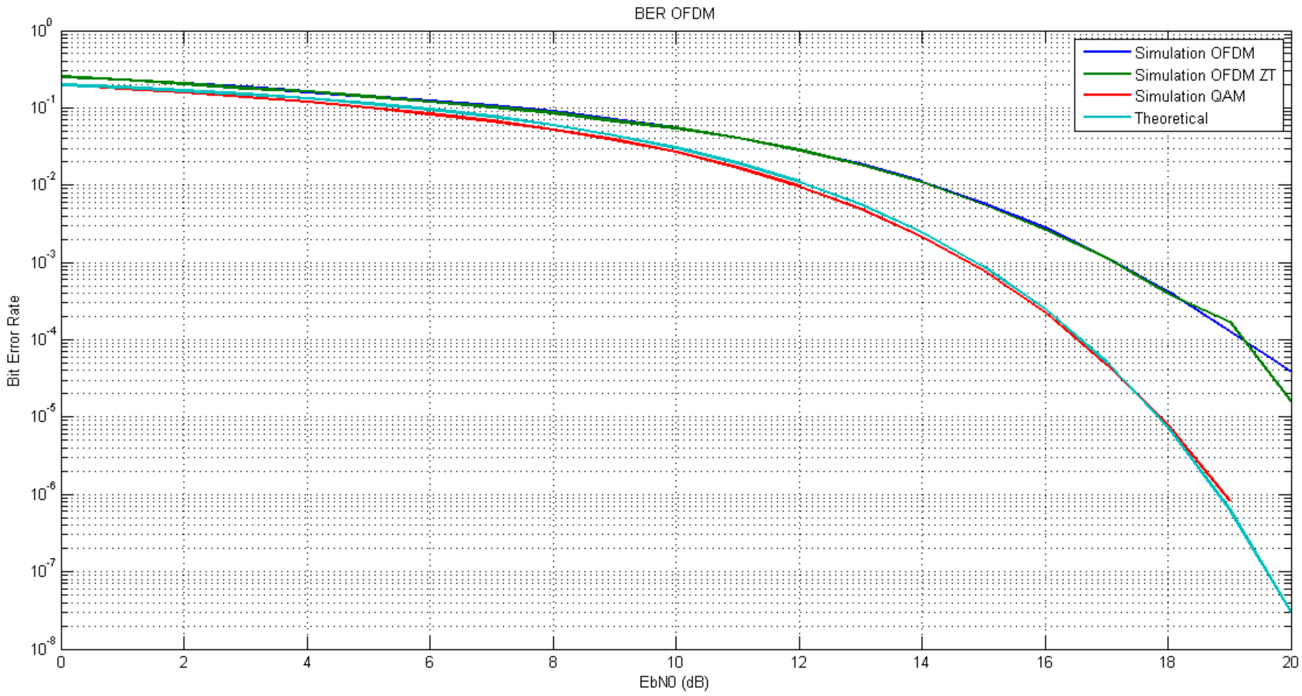

Figure 8.3.2.A – BER vs E_bN_0 with channel estimation (2 symbols)

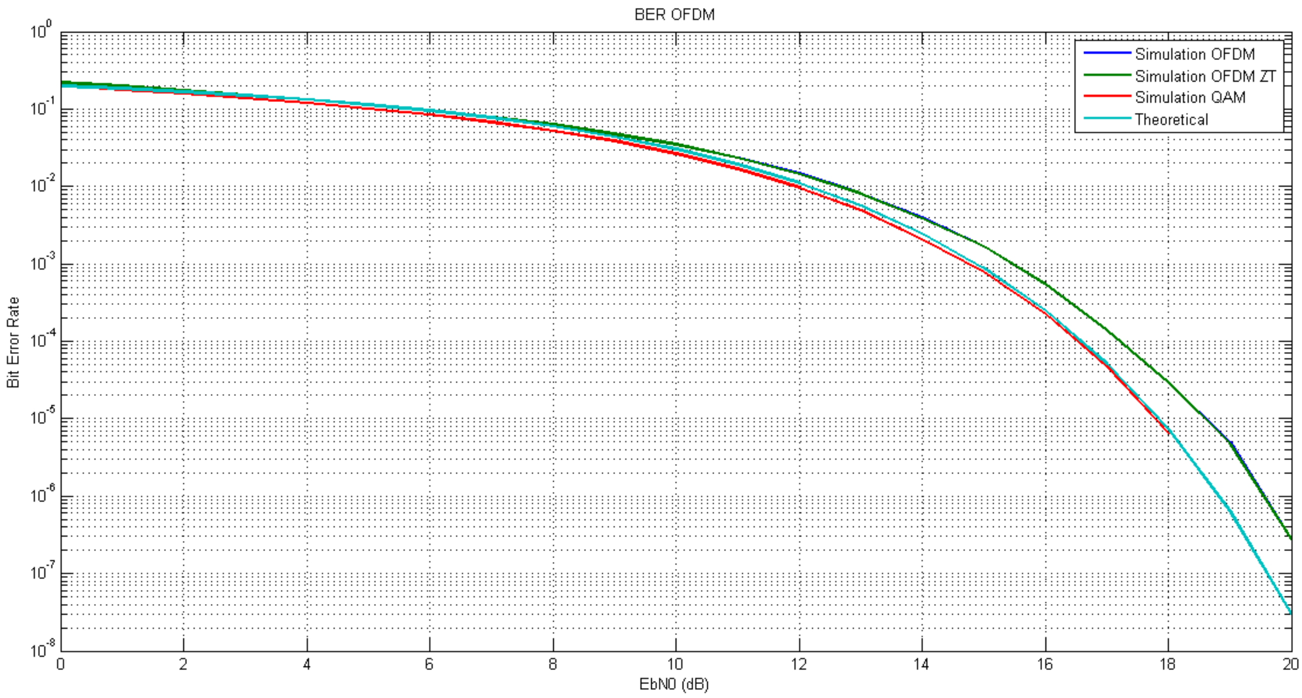

Figure 8.3.2.B – BER vs EbN0 with channel estimation (20 symbols)

8.3.3 LTE channel models with channel estimation

The multi-path channel models give true value to the channel estimation because without this step the signals deviation is significant with high bit error ratios. The comparison between the two systems working in the different channel models shows the previous estimation error (using two symbols to channel estimation) but now is completely necessary for the transmission to demodulate.

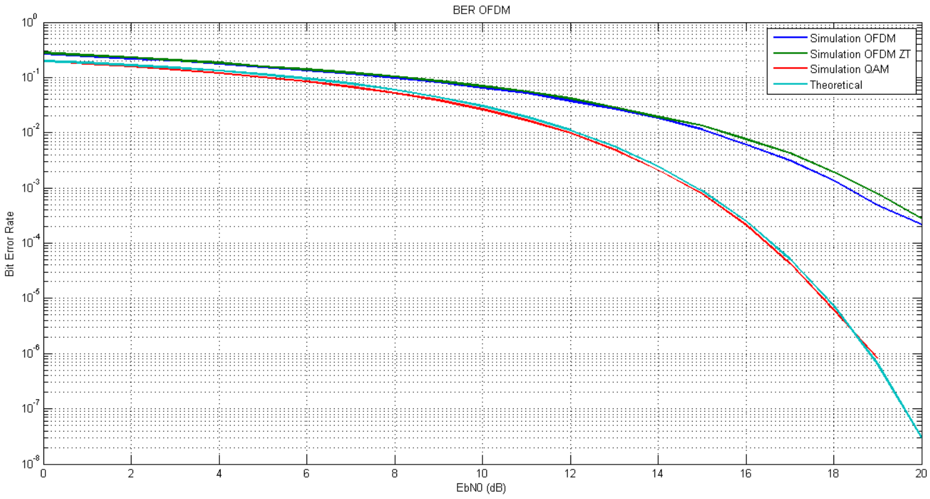

Figure 8.3.3.A – BER vs EbN0 Extended Pedestrian A channel model

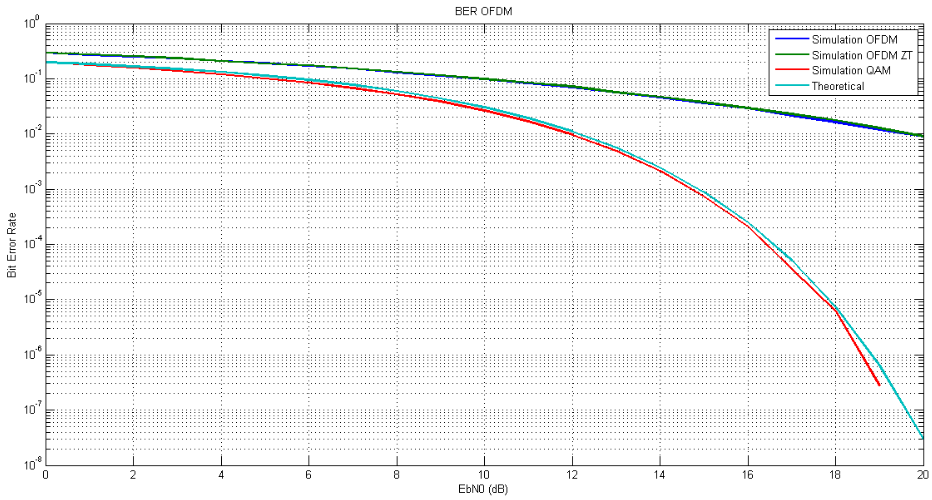

Figure 8.3.3.A – BER vs EbN0 Extended Vehicular A channel model

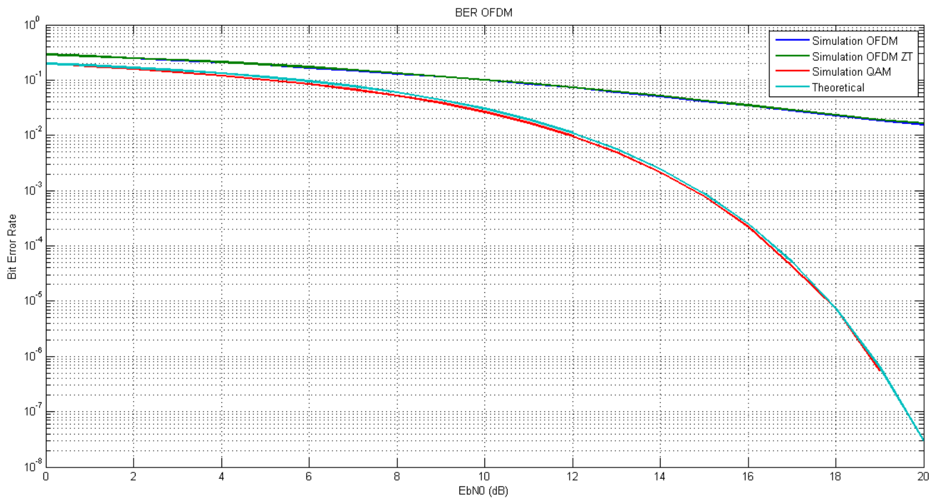

Figure 8.3.3.A – BER vs EbN0 Extended Typical Urban channel model

Although the channel estimation can improve using more symbols the improvement is less representative as in the single-path simulation. Comparing the two systems it shows that the OFDM with Cyclic Prefix works a little better with this channel estimation models but the results are still very close in terms of Bit Error Rate. The OFDM ZT present the disadvantage of not be able to discard the ZT samples at the demodulation step so it have to account for more samples than the OFDM CP model.

8.3.4 Waveforms

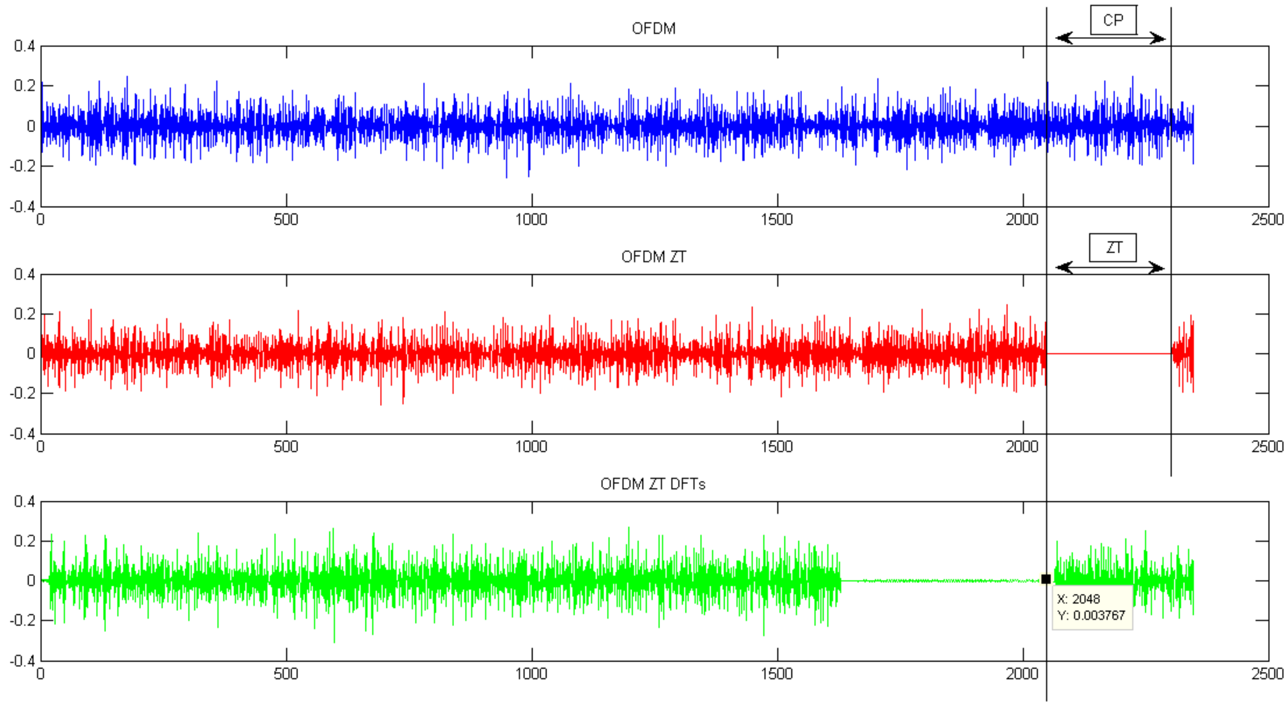

Figure 8.3.4.A – OFDM waveforms

The waveforms of the OFDM CP and the OFDM ZT have similar aspects. The length of the OFDM symbol in these cases is 2304 samples, 2048 samples from the IFFT and 1/8 of this length for the Cyclic Prefix and Zero Tail samples. After the 2304 samples the figure shows the beginning of the next OFDM symbol.

The last system is based in the DFT-spread model which uses the time domain zeros in another FFT block and result in an OFDM symbol length of 2048. The system have to use less data carriers, occupied by the zeros, to maintain the same bandwidth as the other two systems. The figure shows the zero header and the Zero Tail of the signal.

8.3.5 Spectrum

Analyzing the systems' spectrums it can be shown that the OFDM CP and OFDM ZT models have very similar frequency responses. The differences between the two spectrums are in the low power values of guard carriers, it shows that the Zero Tail based system oscillates around -300 dB and -50 dB instead of -100 dB and -50 dB. But the representative values of the response are the high power values of the spectrum that show the similarity between the two models.

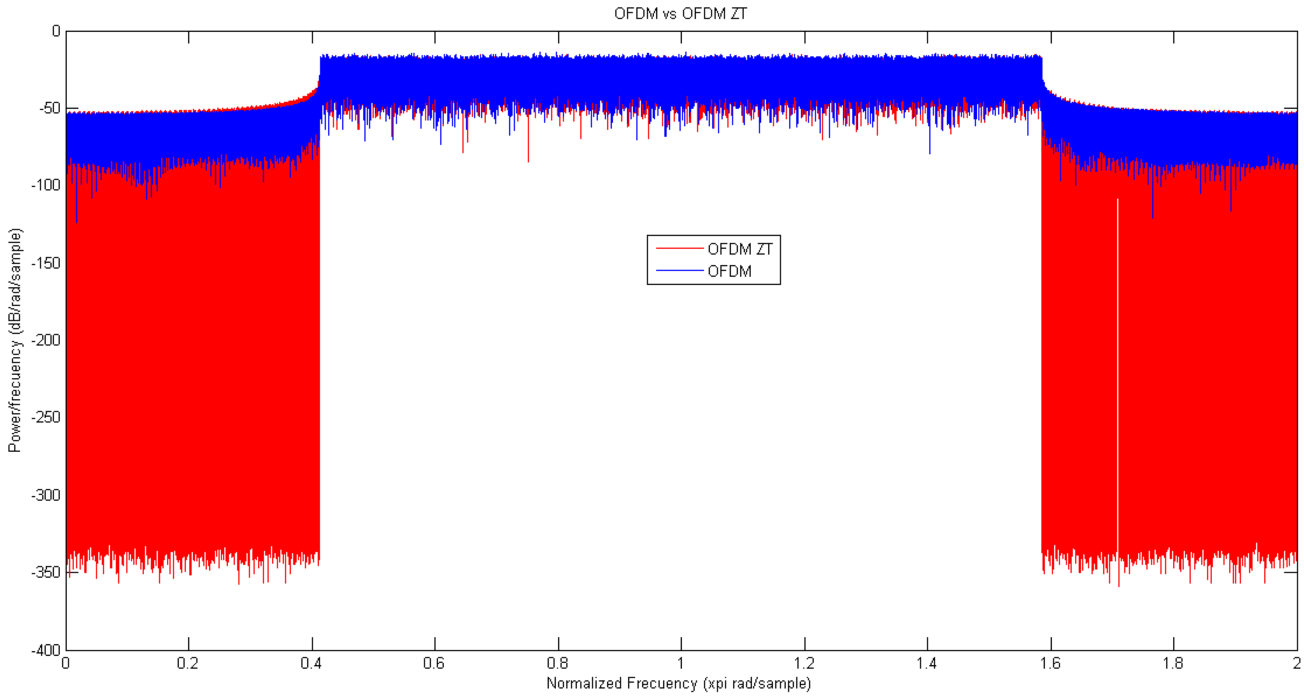

Figure 8.3.5.A – OFDM vs OFDM ZT spectrum

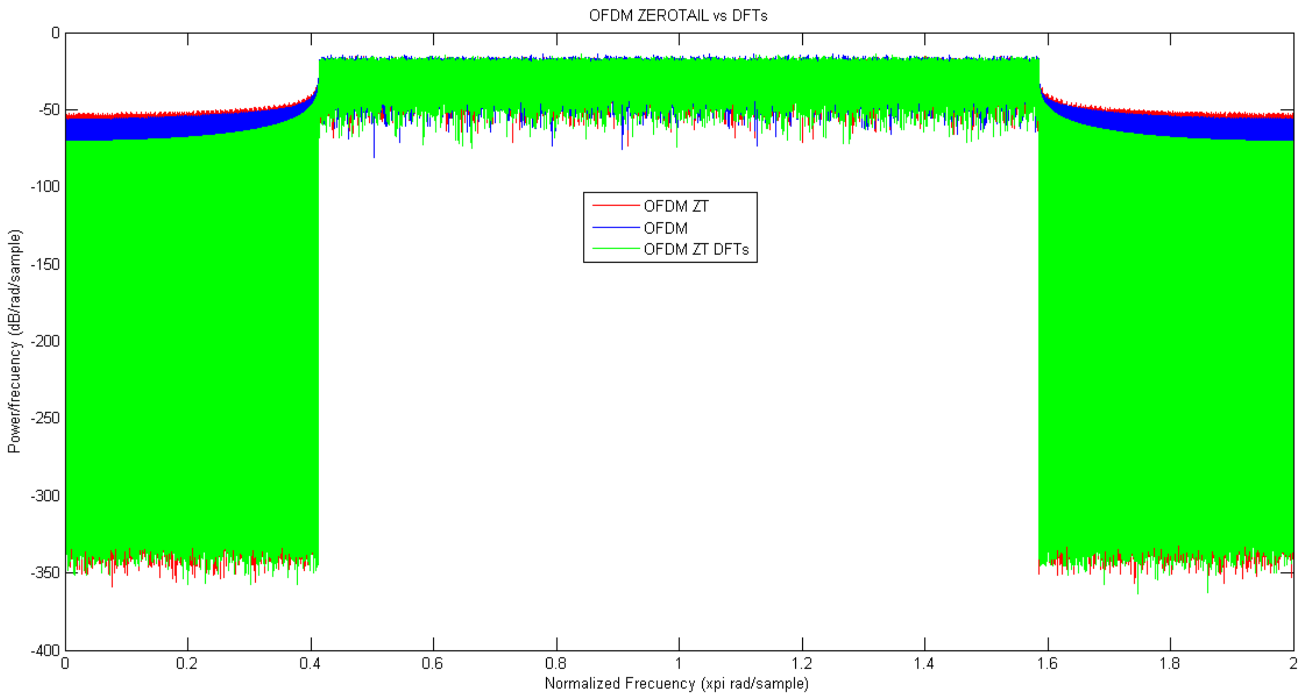

Figure 8.3.5.C – OFDM vs OFDM ZT vs OFDM DFT-spread ZT spectrum

Analyzing the OFDM DFT-s ZT spectrum it reaches lower values, a lower power shoulder than the previous systems. This system improves the spectrum performance of the OFDM signal only using the FFT processing of the zero samples witch is a reasonable cost in a digital communication system. It's shown in *Figure 6.3.5.C* that the maximum values of the shoulders are around -70 dB instead of -50 dB.

9 Conclusion

This study serves as a window to an understanding of the experimenting process using *MATLAB* simulations. All in all the source code is a great value to future experimentation. The OFDM model is a solid code which allows all kinds of modifications that can be used as well in a didactic approach. This was the main idea for this initial source code, to create a reference model.

The OFDM Zero Tail idea comes in the form of a simple improvement of the OFDM model and ends in a step in the middle of achieving the improved waveform for the future mobile generations. The introduction of the zeros improves the signal power relation and free the system of redundant data of each symbol. Once this model is tested it, can be shown why the solution is not that simple: the standard OFDM works equally or better in all the situations when the Bit Error Ratio is involved.

However, this simple modification allows us to go further in the Zero Tail waveform with the DFT-spread model. This system has important spectrum improvements and can provide better coexistence adjacent channels. The model is still under construction lacking a demodulation source code and a proper channel estimation to the LTE channels. Although it can be tested with the full system the waveform transmission shows real improvements to take advantage. The complete design of a OFDM DFT-spread Zero Tail system can be a project based on the source code develop during this report and be a definite test for this new waveform and its future implementation in real communication systems.

The arguments given above prove that the Zero Tail based waveforms can outperformed the actual OFDM systems and are a solid case in the future development of mobile networks.

List of Acronyms

- AWGN — **A**dditive **W**hite **G**aussian **N**oise
- BER — **B**it **E**rror **R**atio
- BW — Bandwidth
- CDMA2000 — **C**ode **D**ivision **M**ultiple **A**ccess 2000
- CP — **C**yclic **P**refix
- DFT — **D**iscrete **F**ourier **T**ransform
- E_bN_0 — Bit energy to noise ratio
- EDGE — **E**nhanced **D**ata Rates for **G**SM **E**volution
- EGPRS — **E**nhanced **G**eneral **P**acket **R**adio **S**ervice
- EPA — **E**xtended **P**edestrian **A**
- ETSI — **E**uropean **T**elecommunications **S**tandards **I**nstitute
- ETU — **E**xtended **T**ypical **U**rban
- EVA — **E**xtended **V**ehicular **A**
- EV-DO — **E**volution-**D**ata **O**ptimized
- FFT — **F**ast **F**ourier **T**ransform
- GPRS — **G**eneral **P**acket **R**adio **S**ervice
- GSM — **G**lobal **S**ystem for **M**obile
- HSDPA — **H**igh-**S**peed **D**ownload **P**acket **A**ccess
- HSPA — **H**igh-**S**peed **P**acket **A**ccess
- HSPA+ — Evolved **H**igh-**S**peed **P**acket **A**ccess
- HSUPA — **H**igh-**S**peed **U**plink **P**acket **A**ccess
- IFFT — **I**nverse **F**ast **F**ourier **T**ransform
- IoT — Internet of Things
- IP — **I**nternet **P**rotocol
- ISI — **I**nter**S**ymbol **I**nterference
- IS-95 — **I**nterim **S**tandard 95
- ITU — **I**nternational **T**elecommunication **U**nion
- I/Q — **I**n-phase / **Q**uadrature
- LTE — **L**ong **T**erm **E**volution
- MIMO — **M**ultiple-**I**nput **M**ultiple-**O**utput
- OFDM — **O**rthogonal **F**requency-**D**ivision **M**ultiplexing
- OFDM CP — **O**rthogonal **F**requency-**D**ivision **M**ultiplexing with **C**yclic **P**refix
- OFDM ZT — **O**rthogonal **F**requency-**D**ivision **M**ultiplexing with **Z**ero **T**ail
- OFDM DFT-spread ZT — OFDM using **D**iscrete **F**ourier **T**ransform spread with **Z**ero **T**ail
- QAM — **Q**uadrature **A**mplitude **M**odulation
- QoS — **Q**uality **o**f **S**ervice
- SAE — **S**ystem **A**rchitecture **E**volution
- SNR — **S**ignal to **N**oise **R**atio
- UMTS — **U**niversal **M**obile **T**elecommunication **S**ystem
- ZT — **Z**ero **T**ail
- 1G — First Generation of Mobile Networks

- 2G Second Generation of Mobile Networks
- 3G Third Generation of Mobile Networks
- 3GPP 3rd Generation Partnership Project
- 3GPP2 3rd Generation Partnership Project 2
- 4G Fourth Generation of Mobile Networks (LTE systems)
- 5G Fifth Generation of Mobile Networks

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(17/6/2015)

Annex

MATLAB source code

Contents

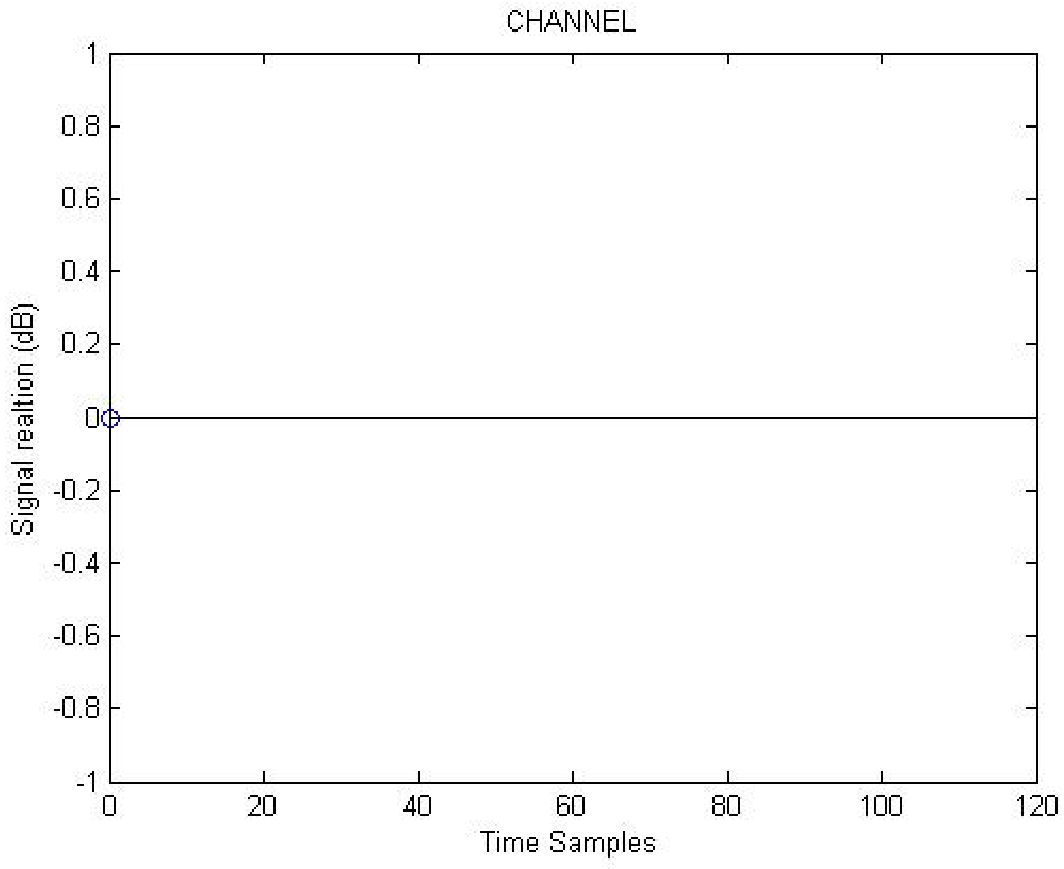

```
%-------------------------------------------------------------------------
%   Javier Celada Muñoz
%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%-------------------------------------------------------------------------

clear all
close all
```

INPUT DATA

```
M = 64;                                 % Size of signal constellation
k = log2(M);                            % Number of bits per symbol
N = 1024;                               % Number of total carriers
usedN = 600;                            % Number of data carriers
unusedN = N-usedN;                      % Number of guard carriers

nSymbOFDM = 100;                        % Number of OFDM Symbols input
n = usedN*k*nSymbOFDM;                  % Number of bits

CP = N/8;                               % Cyclic Prefix length samples
ZT = N/8;                               % Zero Tail length samples

nSymbEst = 2;                           % Number of channel estimation OFDM symbols

EbN0_dB = 30;                           % Bit energy to noise ratio of the simulation
disp('EbN0 dB FOR ALL TRANSMISSIONS:');
disp(EbN0_dB);

t = 0:1:120;                            % Time vector to represent multi-path channel
BW = 20e6;  % Hz                        % Bandwidth of the system
Ts = (1/BW)*1e9; %ns                    % Sampling period

% Intialization
HdB = -inf.*ones(1,length(t));          % Multi-path channel

% Different channel models
%   Uncoment the choosen one and coment the rest to avoid overwrite
%-------------------------------------------------------------------------

% Single-path Channel
HdB(1) = 0;

% % [EPA] Extended Pedestrian A model
% HdB(1) = 0;
% HdB(ceil(51/Ts)) = -1;
```

```
% HdB(ceil(71/Ts)) = -2;
% HdB(ceil(91/Ts)) = -3;
% HdB(ceil(111/Ts)) = -8;
% HdB(ceil(191/Ts)) = -17.2;
% HdB(ceil(411/Ts)) = -20.8;

% % [EVA] Extended Vehicular A model
% HdB(1) = 0;
% HdB(ceil(51/Ts)) = -1.5;
% HdB(ceil(151/Ts)) = -1.4;
% HdB(ceil(311/Ts)) = -3.6;
% HdB(ceil(371/Ts)) = -0.6;
% HdB(ceil(711/Ts)) = -9.1;
% HdB(ceil(1091/Ts)) = -7;
% HdB(ceil(1731/Ts)) = -12;
% HdB(ceil(2511/Ts)) = -16.9;

% % [ETU] Extended Typical Urban model
% HdB(1) = -1;
% HdB(ceil(51/Ts)) = -1;
% HdB(ceil(121/Ts)) = -1;
% HdB(ceil(201/Ts)) = 0;
% HdB(ceil(231/Ts)) = 0;
% HdB(ceil(501/Ts)) = 0;
% HdB(ceil(1601/Ts)) = -3;
% HdB(ceil(2301/Ts)) = -5;
% HdB(ceil(5001/Ts)) = -7;

%-----------------------------------------------------------------------

H = 10.^(HdB/10);                                % Convert channel taps to natural values

figure
stem(t,HdB)
title('CHANNEL')
xlabel('Time Samples')
ylabel('Signal realtion (dB)')

% Theoretical Bit Erro Rate
EbN0 = 10.^(EbN0_dB/10);
SER_MQAM = 2*erfc(sqrt((3*k*EbN0)/(2*(M-1))));
BER_MQAM = SER_MQAM./k;

disp('THEORETICAL BER');
disp(BER_MQAM);

% Input bits
dataIn = randi([0 1],n,1);                       % Generate vector of random binary data

%-----------------------------------------------------------------------
%   All the simulations have the same input data to compare between them.
%   Uncoment the whole section (%% OFDM______) to simulate
%-----------------------------------------------------------------------
```

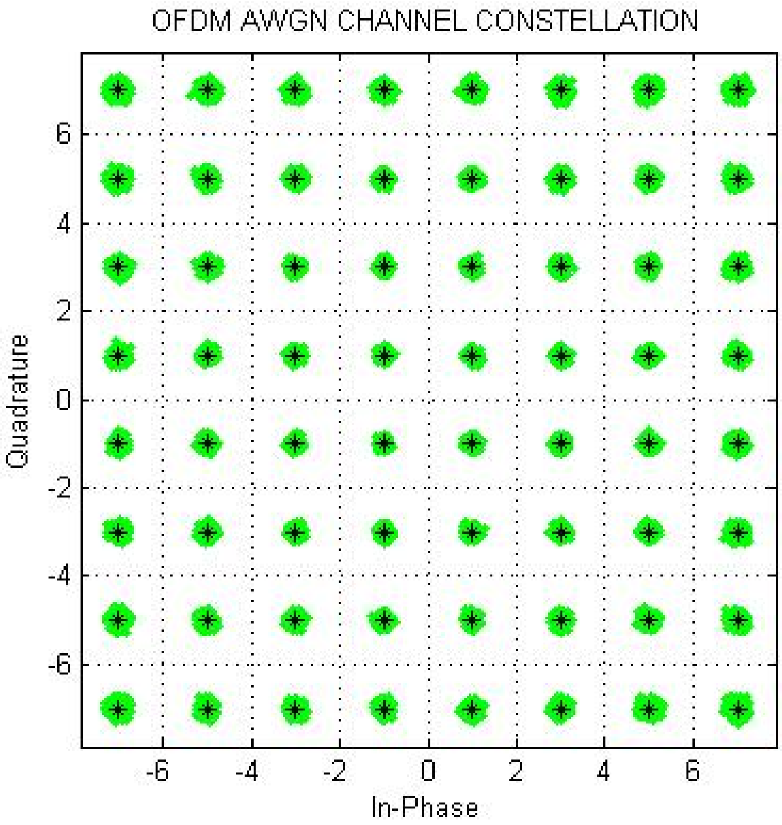
```
EbN0 dB FOR ALL TRANSMISSIONS:
    30

THEORETICAL BER
   1.4232e-64
```



OFDM CHANNEL FIXED SIMULATION

```
% CHANNEL ESTIMATION ---------------------------------------------------
[channelCorrection] = CHANNEL_ESTIMATION(H,nSymbEst,EbN0_dB,k,N,usedN,CP);

% TX -------------------------------------------------------------------
[ofdm , dataMod] = TX_OFDM(dataIn,M,N,usedN,CP);

% CHANNEL ---------------------------------------------------------------
[ofdmChannel] = CHANNEL_OFDM(ofdm, H);

% NOISE -----------------------------------------------------------------
[ofdmAWGN] = AWGN_OFDM(EbN0_dB,ofdmChannel,k,N,usedN,CP);

% RX -------------------------------------------------------------------
[dataInRx , dataModRxFixed] = RX_CHANNEL_OFDM...
    (ofdmAWGN,M,N,usedN,CP,channelCorrection);

% BER-------------------------------------------------------------------
[~, BER] = biterr(dataIn,dataInRx);            % Calculate BER comparing output/input
disp('BER OFDM CHANNEL FIXED');
disp(BER);

% Constellation ---------------------------------------------------------
sPlotFig = scatterplot(dataModRxFixed,1,0,'g.');
grid on
hold on
scatterplot(dataMod,1,0,'k*',sPlotFig)
title('OFDM AWGN CHANNEL CONSTELLATION')
```

```
BER OFDM CHANNEL FIXED
     0
```

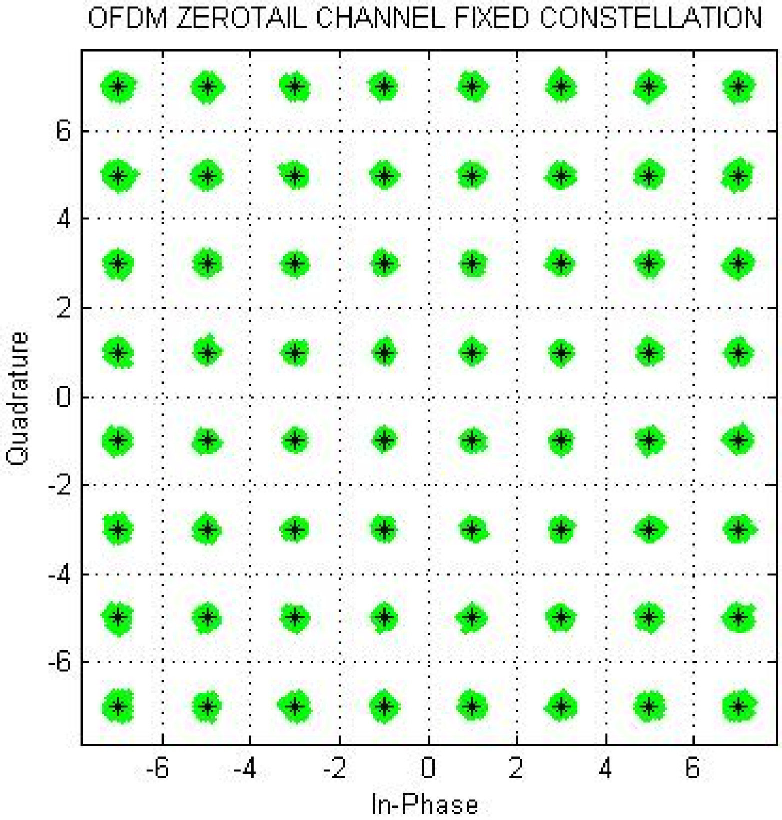


OFDM ZEROTAIL CHANNEL FIXED SIMULATION

```
% CHANNEL ESTIMATION ----------------------------------------------------
[channelCorrection] = CHANNEL_ESTIMATION_ZEROTAIL...
    (H,nSymbEst,EbN0_dB,k,N,usedN,ZT);

% TX ----------------------------------------------------------------------
[ofdmZT , dataMod] = TX_OFDM_ZEROTAIL(dataIn,M,N,usedN,ZT);

% CHANNEL -----------------------------------------------------------------
[ofdmChannel] = CHANNEL_OFDM(ofdmZT, H);

% NOISE -------------------------------------------------------------------
[ofdmAWGN] = AWGN_OFDM(EbN0_dB,ofdmChannel,k,N,usedN,ZT);

% RX ----------------------------------------------------------------------
[dataInRx , dataModRxFixed] = RX_CHANNEL_OFDM_ZEROTAIL...
    (ofdmAWGN,M,N,usedN,ZT,channelCorrection);

% BER---------------------------------------------------------------------
[~, BER] = biterr(dataIn,dataInRx);            % Calculate BER comparing output/input
disp('BER OFDM ZEROTAIL CHANNEL FIXED');
disp(BER);

% Constellation -----------------------------------------------------------
sPlotFig = scatterplot(dataModRxFixed,1,0,'g.');
hold on
```

```
grid on
scatterplot(dataMod,1,0,'k*',sPlotFig)
title('OFDM ZEROTAIL CHANNEL FIXED CONSTELLATION')
```

```
BER OFDM ZEROTAIL CHANNEL FIXED
     0
```

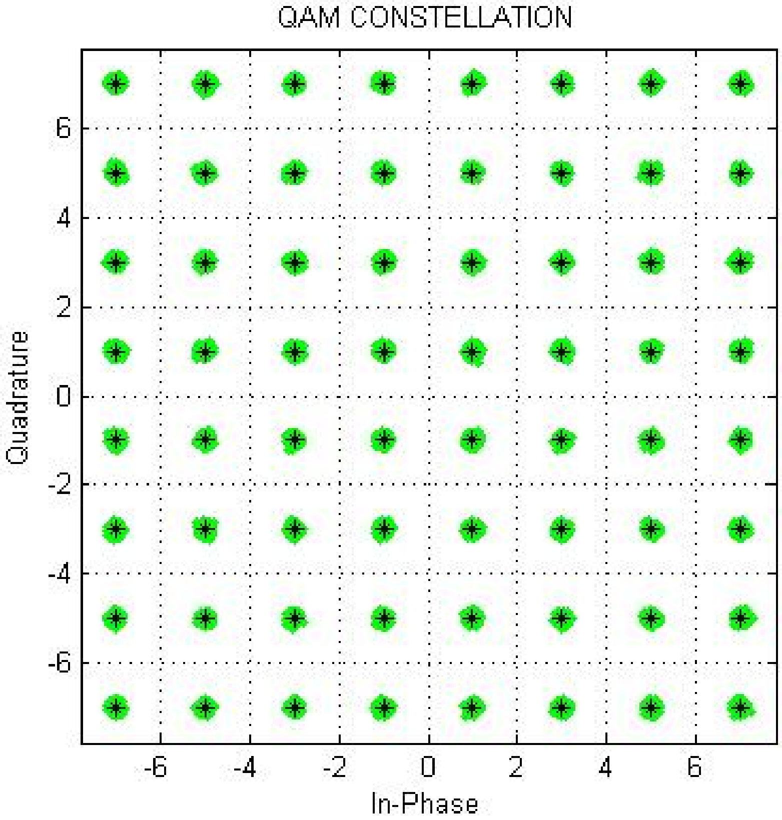


QAM

```
% MODUALTION---------------------------------------------------------------
% Reshape data into binary 4-tuples
dataInMatrix = reshape(dataIn,length(dataIn)/k,k);
% Convert to integers
dataSymbolsIn = bi2de(dataInMatrix);
% Modulate the data with Gray code
dataMod = qammod(dataSymbolsIn,M,0,'gray');

% NOISE -------------------------------------------------------------------
% Signal to noise ratio
snrdB = EbN0_dB + 10*log10(k);
% AWGN channel
dataModNoise = awgn(dataMod,snrdB,'measured');

% Demodulate with Gray code
dataSymbolsInRx = qamdemod(dataModNoise,M,0,'gray');
% Convert to binary data
dataInMatrixRx = de2bi(dataSymbolsInRx);
% Reshape into a binary vector
dataInRx = reshape (dataInMatrixRx,size(dataInMatrixRx,1)...
    *size(dataInMatrixRx,2),1);
```

```
% BER-----------------------------------------------------------------------
[~, BER] = biterr(dataIn,dataInRx);                    % Calculate BER comparing output/input
disp('BER QAM');
disp(BER);

% Constellation -------------------------------------------------------------
sPlotFig = scatterplot(dataModNoise,1,0,'g.');
hold on
grid on
scatterplot(dataMod,1,0,'k*',sPlotFig)
title('QAM CONSTELLATION')
```

```
BER QAM
     0
```



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Contents


```
%--------------------------------------------------------------------------
%   Javier Celada Muñoz
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%
%   Final Project
%   Simulation of waveforms for 5G systems
%--------------------------------------------------------------------------

close all
clear all
```
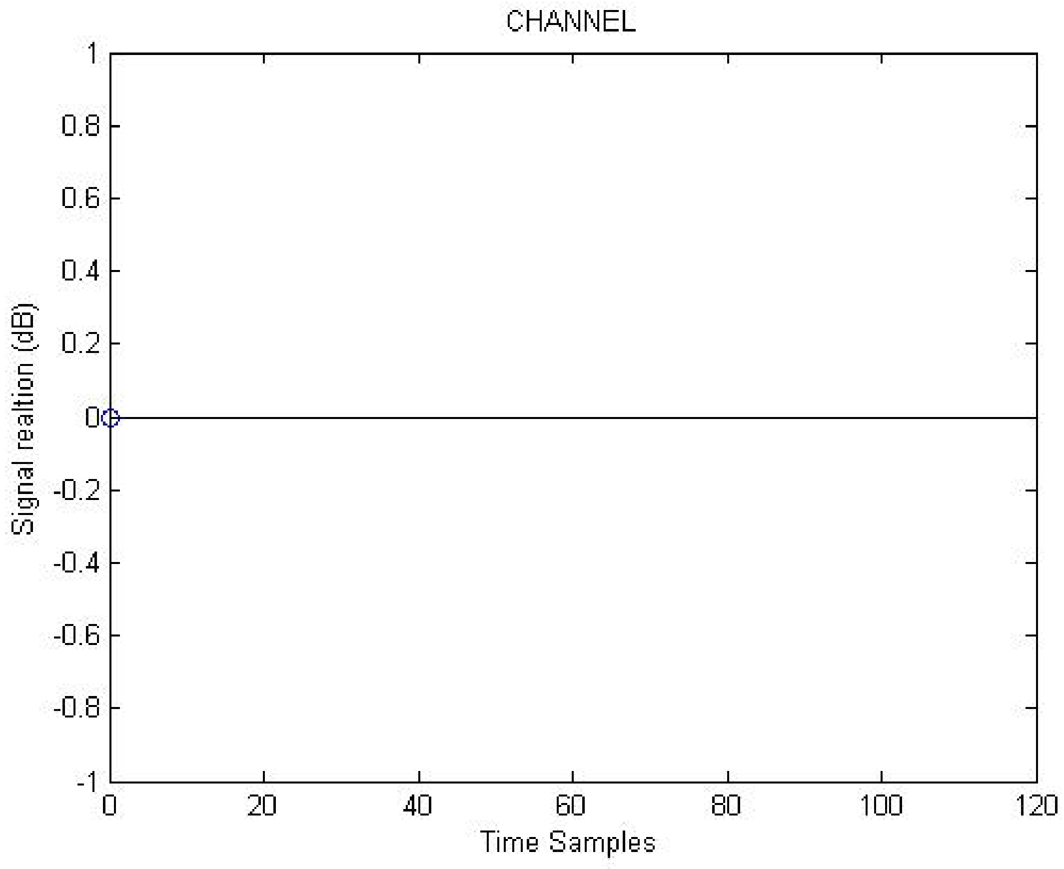

INPUT DATA

```
M = 64;                                 % Size of signal constellation
k = log2(M);                            % Number of bits per symbol
N = 1024;                               % Number of total carriers
usedN = 600;                            % Number of data carriers
unusedN = N-usedN;                      % Number of guard carriers

nSymbOFDM = 1000;                       % Number of OFDM Symbols input
n = usedN*k*nSymbOFDM;                  % Number of bits

CP = N/8;                               % Cyclic Prefix length samples
ZT = N/8;                               % Zero Tail length samples

nSymbEst = 2;                           % Number of channel estimation OFDM symbols

t = 0:1:120;                            % Time vector to represent multi-path channel
BW = 20e6;  % Hz                        % Bandwidth of the system
Ts = (1/BW)*1e9; %ns                    % Sampling period

% EbN0 vector to generate the BER curve
EbN0_dB = 0:1:20;                       % Bit energy to noise ratio of the simulation

% Intialization
HdB = -inf.*ones(1,length(t));          % Multi-path channel
SER = ones(1,length(EbN0_dB)).*inf;     % Symbol Error Rate
BER = ones(1,length(EbN0_dB)).*inf;     % Bit Error Rate OFDM
BER_ZT = ones(1,length(EbN0_dB)).*inf;  % Bit Error Rate OFDM-Zero Tail
BER_QAM = ones(1,length(EbN0_dB)).*inf; % Bit Error Rate QAM

% Different channel models
%   Uncoment the choosen one and coment the rest to avoid overwrite
%--------------------------------------------------------------------------

% Single-path channel
HdB(1) = 0;
```

```
% % [EPA] Extended Pedestrian A model
% HdB(1) = 0;
% HdB(ceil(51/Ts)) = -1;
% HdB(ceil(71/Ts)) = -2;
% HdB(ceil(91/Ts)) = -3;
% HdB(ceil(111/Ts)) = -8;
% HdB(ceil(191/Ts)) = -17.2;
% HdB(ceil(411/Ts)) = -20.8;

% % [EVA] Extended Vehicular A model
% HdB(1) = 0;
% HdB(ceil(51/Ts)) = -1.5;
% HdB(ceil(151/Ts)) = -1.4;
% HdB(ceil(311/Ts)) = -3.6;
% HdB(ceil(371/Ts)) = -0.6;
% HdB(ceil(711/Ts)) = -9.1;
% HdB(ceil(1091/Ts)) = -7;
% HdB(ceil(1731/Ts)) = -12;
% HdB(ceil(2511/Ts)) = -16.9;

% % [ETU] Extended Typical Urban model
% HdB(1) = -1;
% HdB(ceil(51/Ts)) = -1;
% HdB(ceil(121/Ts)) = -1;
% HdB(ceil(201/Ts)) = 0;
% HdB(ceil(231/Ts)) = 0;
% HdB(ceil(501/Ts)) = 0;
% HdB(ceil(1601/Ts)) = -3;
% HdB(ceil(2301/Ts)) = -5;
% HdB(ceil(5001/Ts)) = -7;

%------------------------------------------------------------------------

H = 10.^(HdB/10);                                % Convert channel taps to natural values

figure
stem(t,HdB)
title('CHANNEL')
xlabel('Time Samples')
ylabel('Signal realtion (dB)')

% Input bits
dataIn = randi([0 1],n,1);                       % Generate vector of random binary data

%------------------------------------------------------------------------
%   All the simulations have the same input data to compare between them.
%   Uncoment the whole section (%% OFDM______) to simulate
%------------------------------------------------------------------------
```



OFDM

```
% TX --------------------------------------------------------------------
[ofdm , dataMod] = TX_OFDM(dataIn,M,N,usedN,CP);

% NOISE -----------------------------------------------------------------


for z=1:length(EbN0_dB)

    [channelCorrection] = CHANNEL_ESTIMATION...
        (H,nSymbEst,EbN0_dB(z),k,N,usedN,CP);

    [ofdmChannel] = CHANNEL_OFDM(ofdm,H);

    [ofdmAWGN] = AWGN_OFDM(EbN0_dB(z),ofdmChannel,k,N,usedN,CP);

    [dataInRx , dataModRx] = RX_CHANNEL_OFDM...
        (ofdmAWGN,M,N,usedN,CP,channelCorrection);

    dataSymbolsIn = qamdemod(dataMod,M,0,'gray');
    dataSymbolsInRx = qamdemod(dataModRx,M,0,'gray');

    [SER(z)] = sum(dataSymbolsIn ~= dataSymbolsInRx)./...
        length(dataSymbolsIn);
    [~, BER(z)] = biterr(dataIn,dataInRx);

end
```

OFDM ZT

```
% TX --------------------------------------------------------------------
```

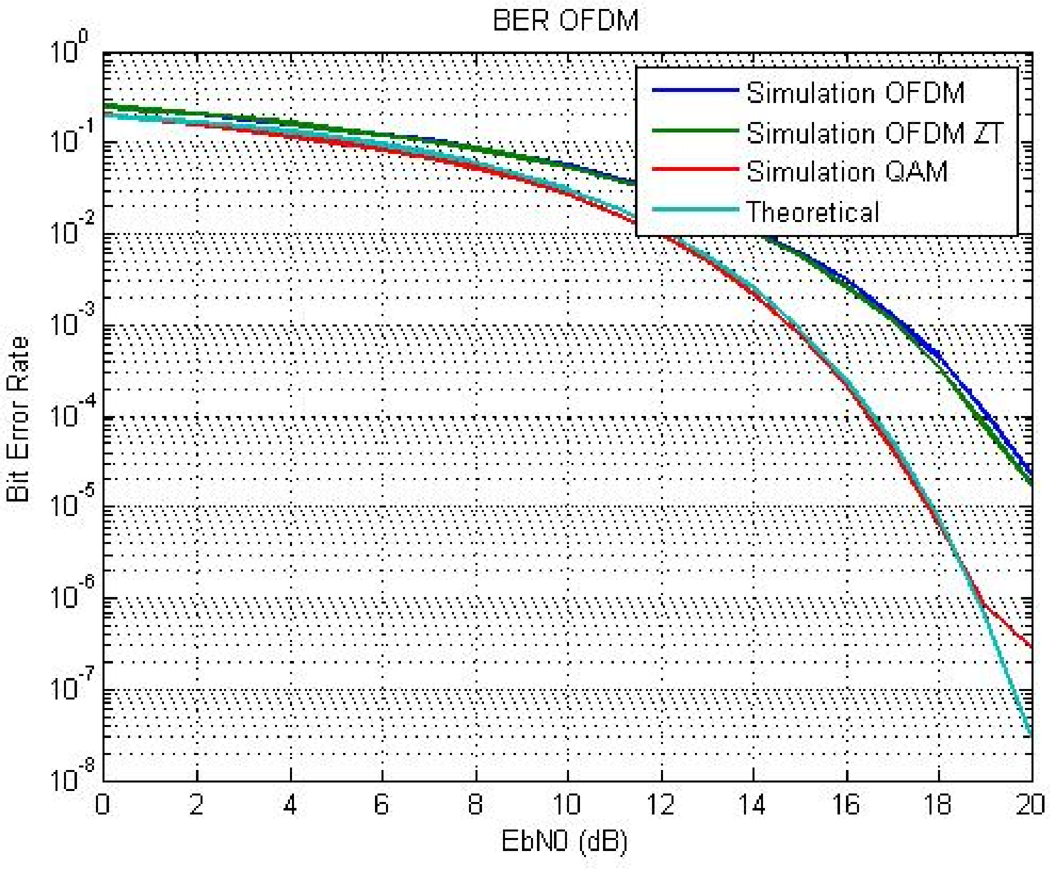
```
[ofdmZT , dataModZT] = TX_OFDM_ZEROTAIL(dataIn,M,N,usedN,ZT);

% NOISE -------------------------------------------------------------------

for z=1:length(EbN0_dB)

    [channelCorrectionZT] = CHANNEL_ESTIMATION_ZEROTAIL...
        (H,nSymbEst,EbN0_dB(z),k,N,usedN,ZT);

    [ofdmChannelZT] = CHANNEL_OFDM(ofdmZT,H);

    [ofdmAWGNZT] = AWGN_OFDM(EbN0_dB(z),ofdmChannelZT,k,N,usedN,ZT);

    [dataInRxZT , dataModRxZT] = RX_CHANNEL_OFDM_ZEROTAIL...
        (ofdmAWGNZT,M,N,usedN,ZT,channelCorrectionZT);

    dataSymbolsZT = qamdemod(dataModZT,M,0,'gray');
    dataSymbolsRxZT = qamdemod(dataModRxZT,M,0,'gray');

    [SER_ZT(z)] = sum(dataSymbolsZT ~= dataSymbolsRxZT)./...
        length(dataSymbolsZT);
    [~, BER_ZT(z)] = biterr(dataIn,dataInRxZT);

end
```

QAM

```
% MODUALTION--------------------------------------------------------------
% Reshape data into binary 4-tuples
dataInMatrix = reshape(dataIn,length(dataIn)/k,k);
% Convert to integers
dataSymbolsIn = bi2de(dataInMatrix);
% Modulate the data with Gray code
dataMod = qammod(dataSymbolsIn,M,0,'gray');

% NOISE -------------------------------------------------------------------

for z=1:length(EbN0_dB)

    % Signal to noise ratio
    snrdB = EbN0_dB(z) + 10*log10(k);
    % AWGN channel
    dataModNoise = awgn(dataMod,snrdB,'measured');

    % Demodulate with Gray code
    dataSymbolsInRx = qamdemod(dataModNoise,M,0,'gray');
    % Convert to binary data
    dataInMatrixRx = de2bi(dataSymbolsInRx);
    % Reshape into a binary vector
    dataInRx = reshape (dataInMatrixRx,size(dataInMatrixRx,1)...
        *size(dataInMatrixRx,2),1);

    [SER(z)] = sum(dataSymbolsIn ~= dataSymbolsInRx)./...
        length(dataSymbolsIn);
    [~, BER_QAM(z)] = biterr(dataIn,dataInRx);

end
```

CURVES

```
% Theoretical BER curve
EbN0 = 10.^(EbN0_dB/10);
SER_MQAM = 2*erfc(sqrt((3*k*EbN0)/(2*(M-1))));
BER_MQAM = SER_MQAM./k;                              % Bit Error Rate Theoretical

figure
semilogy(EbN0_dB,[BER;BER_ZT;BER_QAM;BER_MQAM],'LineWidth',2)
grid on;
legend('Simulation OFDM','Simulation OFDM ZT','Simulation QAM','Theoretical');
xlabel('EbN0 (dB)');ylabel('Bit Error Rate');
title('BER OFDM')
```



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Contents


```
%--------------------------------------------------------------------------
%   Javier Celada Muñoz
%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%--------------------------------------------------------------------------

clear all
close all
```

INPUT DATA

```
M = 64;                                     % Size of signal constellation
k = log2(M);                                % Number of bits per symbol
N = 2048;                                   % Number of carriers
usedN = 1200;                               % Number of data carriers
unusedN = N-usedN;                          % number of guard carriers
nSymbOFDM = 100;                            % Number of OFDM Symbols input

n = usedN*k*nSymbOFDM;                      % Input number of bits

CP = N/8;                                   % Cyclic Prefix length
ZT = N/8;                                   % Zero tail length

dataIn = randi([0 1],n,1);                  % Generate vector of binary data
```

OFDM ZERO TAIL DFT-spread ---

```
% TX ----------------------------------------------------------------------
[ofdmZTDFT , ~] = TX_OFDM_ZEROTAIL_DFT(dataIn,M,N,usedN,ZT);
```

```
Discarded last QAM symbols in ZT-DFTs
   112
```

OFDM ZEROTAIL ---

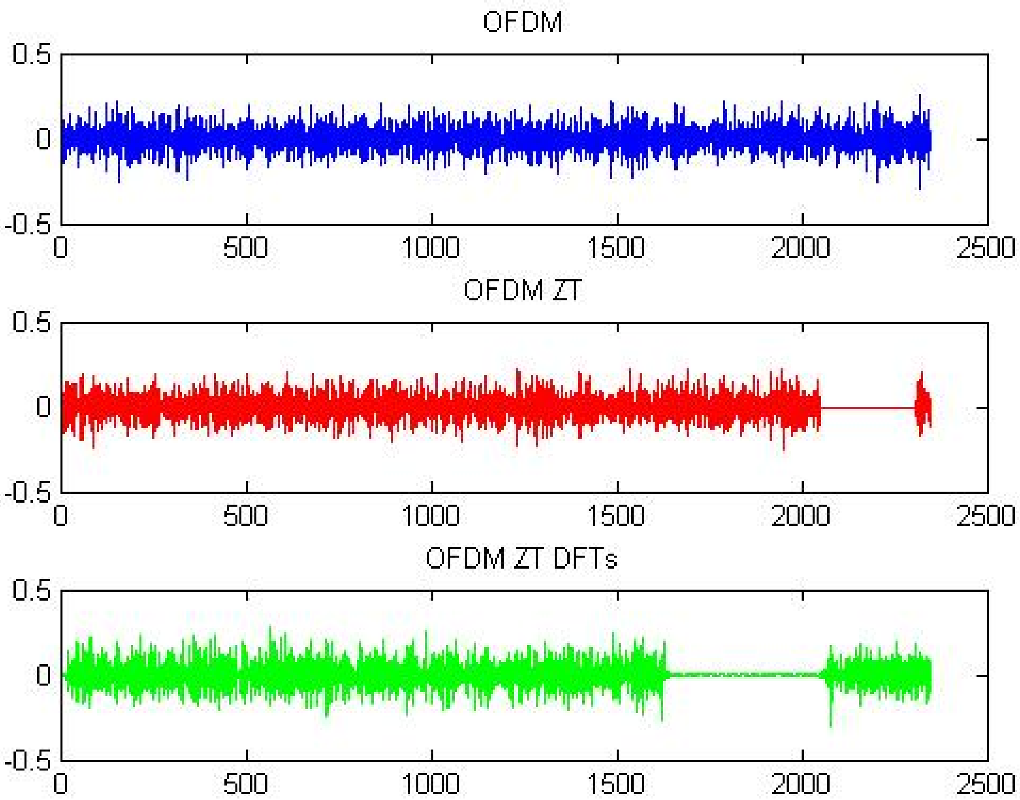
```
% TX ----------------------------------------------------------------------
[ofdmZT , ~] = TX_OFDM_ZEROTAIL(dataIn,M,N,usedN,ZT);
```

OFDM ---

```
% TX ---------------------------------------------------------------------
[ofdm , ~] = TX_OFDM(dataIn,M,N,usedN,CP);
```

Waveforms ---

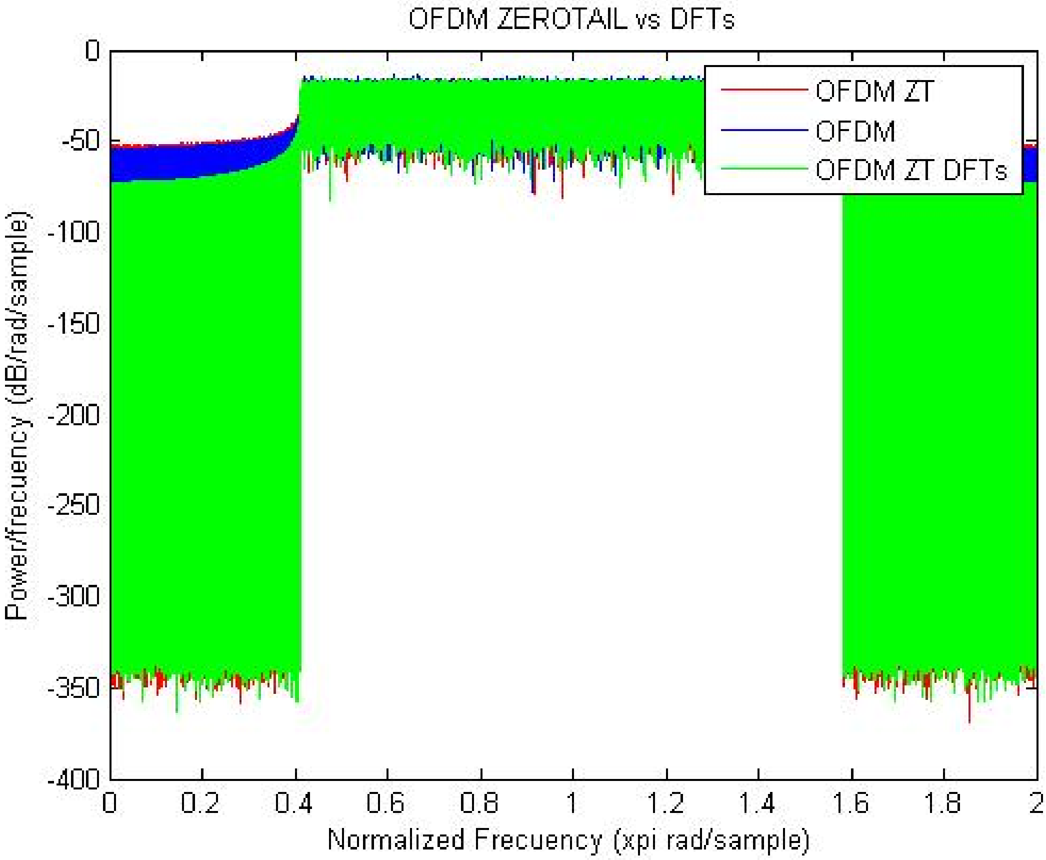
```
figure
subplot(3,1,1)
plot(real(ofdm(1:N+300)))
title('OFDM')
subplot(3,1,2)
plot(real(ofdmZT(1:N+300)),'r')
title('OFDM ZT')
subplot(3,1,3)
plot(real(ofdmZTDFT(1:N+300)),'g')
title('OFDM ZT DFTs')
```



Spectrum ---

```
figure
[pxx,f] = periodogram(ofdmZT);
plot(f/pi,10*log10(pxx),'r')
hold on
[pxx,f] = periodogram(ofdm);
plot(f/pi,10*log10(pxx))
hold on
[pxx,f] = periodogram(ofdmZTDFT);
plot(f/pi,10*log10(pxx),'g')
ylabel('Power/frecuency (dB/rad/sample)')
```

```
xlabel('Normalized Frecuency (xpi rad/sample)')
title('OFDM ZEROTAIL vs DFTs')
legend('OFDM ZT', 'OFDM','OFDM ZT DFTs')
```



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```
%-----------------------------------------------------------------------
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%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%-----------------------------------------------------------------------
%   OFDM THROUGH AWGN CHANNEL
%   Simulation of the effect produced by this type of channel to a OFDM
%   signal.
%
%   [ ofdmAWGN ] = AWGN_OFDM( EbN0_dB , ofdm, k )
%
%   Funcitions returns ofdmNoise (same dimension as ofdm) and needs
%   this parameters input:
%
%   EbN0_dB ->  Bit energy to noise ratio in dB
%   ofdm ->     Chain of OFDM symbols (or one of them)
%   k->         Bits per QAM symbol
%   N->         Number of OFDM carriers
%   usedN->     Number of data carriers
%   CP->        Cyclic prefix lenght (or Zero tail)

function [ ofdmAWGN ] = AWGN_OFDM( EbN0_dB , ofdm, k , N , usedN , CP )

EbN0 = 10^(EbN0_dB/10);
snr = (N/(N+CP))*(usedN/N)*EbN0*k;
snrdB = 10*log10(snr);                              % SNR from EbN0
ofdmAWGN = awgn(ofdm,snrdB,'measured');             % Channel AWGN

% % AWGN addition figure
% figure
% plot(real(ofdmAWGN),'r')
% hold on
% plot(real(ofdm))
% plot(real(ofdmAWGN)-real(ofdm),'g')
% title('OFDM NOISE')
% legend('OFDM AWGN','OFDM','NOISE')

end
```

```
Error using AWGN_OFDM (line 27)
Not enough input arguments.
```

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```
%-----------------------------------------------------------------------------
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%
%   Final Project
%   Simulation of waveforms for 5G systems
%-----------------------------------------------------------------------------
%   CHANNEL ESTIMATION FOR OFDM
%   Estimation of the channel used in the simulation to obtain the
%   correction values for the OFDM carriers to avoid the efect of the
%   multipath channel.
%
%   [ channelCorrection ] = CHANNEL_ESTIMATION( H , nSymbEst, EbN0_dB, k , N , usedN, CP )
%
%   Funcitions returns channelCorrection (Nx1) and needs this parameters input:
%
%   H->         Channel
%   nSymbEst->  Number of OFDM test symbols to do the estimation
%   EbN0_dB->   Bit energy to noise ratio in dB
%   k->         Bits per QAM symbol
%   N->         Number of OFDM carriers
%   usedN->     Number of data carriers
%   CP->        Length of cyclic prefix

function [ channelCorrection ] = CHANNEL_ESTIMATION...
    ( H , nSymbEst, EbN0_dB, k , N ,usedN, CP)

unusedN = N - usedN;

%TX
dataModUsedN = ones(usedN,nSymbEst);                % Data test to send
dataModN = zeros(N,nSymbEst);

ofdm = zeros(size(dataModN,2)*N,1);
ofdmSymbol = zeros(N,size(dataModN,2));
ofdmSymbolCP = zeros(N+CP,size(dataModN,2));

for j=1:size(dataModN,2)
    dataModN(:,j) = vertcat(zeros(unusedN/2,1),dataModUsedN(:,j),zeros(unusedN/2,1));
    % Create Symbol OFDM
    ofdmSymbol(:,j) = ifft(dataModN(:,j),N);
    % Add the cyclic prefix at the beginning of the OFDM Symbol
    ofdmSymbolCP(:,j) = vertcat(ofdmSymbol(N-CP+1:N,j),ofdmSymbol(:,j));
    % Create the vector with all the OFDM symbols
    ofdm((j-1)*length(ofdmSymbolCP)+1:j*length(ofdmSymbolCP)) = ofdmSymbolCP(:,j);
end

%CHANNEL
ofdmChannel = filter (H,1,ofdm);                    % Channel Multipath

%AWGN
EbN0 = 10^(EbN0_dB/10);
snr = (N/(N+CP))*(usedN/N)*EbN0*k;
snrdB = 10*log10(snr);                              % SNR from EbN0
ofdmAWGN = awgn(ofdmChannel,snrdB,'measured');      % Channel AWGN

ofdmSymbolCPRx = reshape (ofdmAWGN,N+CP,length(ofdmAWGN)/(N+CP));
ofdmSymbolRx = ofdmSymbolCPRx(CP+1:end,:);
```

```
dataModNRx = zeros(N,size(ofdmSymbolRx,2));
channelCorrectionMatrix = zeros(N,size(ofdmSymbolRx,2));

for j=1:size(ofdmSymbolRx,2)
    % Info of the CP carriers is ignored
    % dataModNRx = H
    dataModNRx(:,j) = fft(ofdmSymbolRx(:,j),N);
    % X / Y = 1 / H
    channelCorrectionMatrix(:,j)=dataModN(:,j)./dataModNRx(:,j);
end

channelCorrection = mean(channelCorrectionMatrix,2);    % Estimation nSymb

% % Channel estimation figure
% figure
% subplot(4,1,1)
% stem(real(dataModN(:,1)))
% title('Test Data Sent')
% subplot(4,1,2)
% stem(real(dataModNRx(:,1)))
% title('Test Data Received')
% subplot(4,1,3)
% stem(real(channelCorrection))
% title('Channel Correction')
% subplot(4,1,4)
% stem(real(channelCorrection.*dataModNRx(:,1)))
% title('Test Data Received X Channel Correction')
end
```

```
Error using CHANNEL_ESTIMATION (line 29)
Not enough input arguments.
```

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```
%--------------------------------------------------------------------------
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%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%--------------------------------------------------------------------------
%   CHANNEL ESTIMATION FOR OFDM ZEROTAIL
%   Estimation of the channel used in the simulation to obtain the
%   correction values for the OFDM carriers to avoid the efect of the
%   multipath channel.
%
%   [ channelCorrection ] = CHANNEL_ESTIMATION_ZEROTAIL...
%                   ( H , nSymbEst, EbN0_dB, k , N , usedN, ZT )
%
%   Funcitions returns channelCorrection (Nx1) and needs this parameters input:
%
%   H->         Channel
%   nSymbEst->  Number of OFDM test symbols to do the estimation
%   EbN0_dB->   Bit energy to noise ratio
%   k->         Bits per QAM symbol
%   N->         Number of OFDM carriers
%   usedN->     Numer of data carriers
%   ZT->        Length of the zero tail

function [ channelCorrection ] = CHANNEL_ESTIMATION_ZEROTAIL...
    ( H , nSymbEst, EbN0_dB, k , N ,usedN, ZT )

unusedN = N - usedN;

%TX
dataModUsedN = ones(usedN,nSymbEst);            % Data test to send
dataModN = zeros(N,nSymbEst);                   % through the channel

ofdm = zeros(size(dataModN,2)*N,1);
ofdmSymbol = zeros(N,size(dataModN,2));
ofdmSymbolZT = zeros(N+ZT,size(dataModN,2));
zerotail = zeros (ZT,size(dataModN,2));

for j=1:size(dataModN,2)
    dataModN(:,j) = vertcat(zeros(unusedN/2,1),dataModUsedN(:,j),zeros(unusedN/2,1));
    % Create Symbol OFDM
    ofdmSymbol(:,j) = ifft(dataModN(:,j),N);
    % Add the ending zeros
    ofdmSymbolZT(:,j) = vertcat(ofdmSymbol(:,j),zerotail(:,j));
    % Create the vector with all the OFDM symbols
    ofdm((j-1)*length(ofdmSymbolZT)+1:j*length(ofdmSymbolZT)) = ofdmSymbolZT(:,j);
end

%CHANNEL
ofdmChannel = filter (H,1,ofdm);                % Channel Multipath

%AWGN
EbN0 = 10^(EbN0_dB/10);
snr = (N/(N+ZT))*(usedN/N)*EbN0*k;
snrdB = 10*log10(snr);                          % SNR from EbN0
ofdmAWGN = awgn(ofdmChannel,snrdB,'measured');  % Channel AWGN
```

```
%RX
ofdmSymbolZTRx = reshape (ofdmAWGN,N+ZT,length(ofdmAWGN)/(N+ZT));
dataModNRx = zeros(N,size(ofdmSymbolZTRx,2));
channelCorrectionMatrix = zeros(N,size(ofdmSymbolZTRx,2));

for j=1:size(ofdmSymbolZTRx,2)
% Info of the zero carriers is added to the frist ZT ones
    ofdmSymbolZTRx(1:ZT,j) = ofdmSymbolZTRx(1:ZT,j) + ofdmSymbolZTRx(N+1:end,j);
    ofdmSymbolRx = ofdmSymbolZTRx(1:N,:);
    % dataModNRx = H
    dataModNRx(:,j) = fft(ofdmSymbolRx(:,j),N);
    % X / Y = 1 / H
    channelCorrectionMatrix(:,j)=dataModN(:,j)./dataModNRx(:,j);
end

channelCorrection = mean(channelCorrectionMatrix,2);

% % Channel estimation figure
% figure
% subplot(4,1,1)
% stem(real(dataModN(:,1)))
% title('Test Data Sent')
% subplot(4,1,2)
% stem(real(dataModNRx(:,1)))
% title('Test Data Received')
% subplot(4,1,3)
% stem(real(channelCorrection))
% title('Channel Correction')
% subplot(4,1,4)
% stem(real(channelCorrection.*dataModNRx(:,1)))
% title('Test Data Received X Channel Correction')

end
```

```
Error using CHANNEL_ESTIMATION_ZEROTAIL (line 30)
Not enough input arguments.
```

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```
%--------------------------------------------------------------------------
%   Javier Celada Muñoz
%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%--------------------------------------------------------------------------
%   OFDM THROUGH MULTIPATH CHANNEL
%   Simulation of the effect produced by this type of channel to a OFDM
%   signal.
%
%   [ ofdmChannel ] = CHANNEL_OFDM( ofdm , H )
%
%   Funcitions returns ofdmEchoes (same dimension as ofdm) and needs
%   this parameters input:
%   ofdm -> Chain of OFDM symbols (or one of them)
%   H-> Channel

function [ ofdmChannel ] = CHANNEL_OFDM( ofdm , H )

ofdmChannel = filter (H,1,ofdm);                    % OFDM through multi-path channel

end
```

```
Error using CHANNEL_OFDM (line 22)
Not enough input arguments.
```

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```
%-------------------------------------------------------------------------
%   Javier Celada Muñoz
%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%-------------------------------------------------------------------------
%   RECEPTION OF THE OFDM SIGNAL WITH CHANNEL CORRECTION
%   Simulation of the extraction of the OFDM symbols, their useful
%   information and the final chain of QAM symbols to demodulate.
%
%   [ dataInRx,dataModRxFixed ] = RX_CHANNEL_OFDM( ofdm,M,N,usedN,CP,channelCorrection )
%
%   MUST HAVE channelCorrection vector simulated in the function:
%   CHANNEL_ESTIMATION.m
%
%   OUTPUT:
%   dataInRx -> Bit vector obtain from the ofdm signal
%   dataModRxFixed -> QAM symbols inside the carriers OFDM with the
%                     channel correction necessary.
%
%   INPUT:
%   ofdm -> Chain of OFDM symbols
%   M -> Number of symbols of the QAM constellation
%   N -> Number of OFDM carriers
%   usedN -> Number of OFDM data carriers
%   CP -> Length of the cyclic preix
%   channelCorrection -> 1xN vector equivalent to 1/H, the compensation of
%                                               the multipath channel effect.

function [ dataInRx,dataModRxFixed ] = RX_CHANNEL_OFDM( ofdm,M,N,usedN,CP,channelCorrection )

unusedN = N - usedN;

ofdmSymbolCPRx = reshape (ofdm,N+CP,length(ofdm)/(N+CP));
ofdmSymbolRx = ofdmSymbolCPRx(CP+1:end,:);

dataModNRx = zeros(N,size(ofdmSymbolRx,2));
dataModUsedNRx = zeros(usedN,size(ofdmSymbolRx,2));
dataModNRxFixed = zeros(N,size(ofdmSymbolRx,2));

for j=1:size(ofdmSymbolRx,2)
    % Info of the CP carriers is ignored
    % Carries with QAM symbols
    dataModNRx(:,j) = fft(ofdmSymbolRx(:,j),N);
    % Carriers channel fixed
    dataModNRxFixed (:,j) = dataModNRx(:,j).*channelCorrection;
    % Recover data carriers
    dataModUsedNRx(:,j) = dataModNRxFixed(unusedN/2+1:N-unusedN/2,j);
end

% Info of the OFDM carriers to a chain of QAM simbols to get data vector
dataModRxFixed = reshape...
    (dataModUsedNRx,size(dataModUsedNRx,1)*size(dataModUsedNRx,2),1);
dataSymbolsInRx = qamdemod(dataModRxFixed,M,0,'gray');
dataInMatrixRx = de2bi(dataSymbolsInRx);
dataInRx = reshape...
    (dataInMatrixRx,size(dataInMatrixRx,1)*size(dataInMatrixRx,2),1);
```

```
end
```

```
Error using RX_CHANNEL_OFDM (line 34)
Not enough input arguments.
```

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```
%---------------------------------------------------------------------------
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%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%---------------------------------------------------------------------------
%   RECEPTION OF THE OFDM ZEROTAIL SIGNAL WITH MULTIPATH CHANNEL CORRECTION
%   Simulation of the extraction of the OFDM symbols, their useful
%   information and the final chain of QAM symbols to demodulate.
%
%   [ dataInRx,dataModRxFixed ] = ...
%       RX_CHANNEL_OFDM_ZEROTAIL( ofdm,M,N,usedN,ZT,channelCorrection )
%
%   MUST HAVE channelCorrection vector simulated in the function:
%   CHANNEL_ESTIMATION_ZEROTAIL.m
%
%   OUTPUT:
%   dataInRx -> Bit vector obtain from the ofdm signal
%   dataModRxFixed -> QAM symbols inside the carriers OFDM with the
%                     channel correction necessary.
%
%   INPUT:
%   ofdm -> Chain of OFDM symbols
%   M -> Number of symbols of the QAM constellation
%   N -> Number of OFDM carriers
%   usedN -> Number of data OFDM carriers
%   ZT -> Length of the zero tail
%   channelCorrection -> 1xN vector equivalent to 1/H, the compensation of
%                        the multipath channel effect.

function [ dataInRx,dataModRxFixed ] = RX_CHANNEL_OFDM_ZEROTAIL( ofdm,M,N,usedN,ZT,channelCorrec
tion )

unusedN = N - usedN;

ofdmSymbolZTRx = reshape (ofdm,N+ZT,length(ofdm)/(N+ZT));

dataModNRx = zeros(N,size(ofdmSymbolZTRx,2));
dataModUsedNRx = zeros(usedN,size(ofdmSymbolZTRx,2));
dataModNRxFixed = zeros(N,size(ofdmSymbolZTRx,2));

for j=1:size(ofdmSymbolZTRx,2)
    % Info of the zero carriers is added to the frist ZT ones
    ofdmSymbolZTRx(1:ZT,j) = ofdmSymbolZTRx(1:ZT,j) + ofdmSymbolZTRx(N+1:end,j);
    ofdmSymbolRx = ofdmSymbolZTRx(1:N,j);
    % Carries with QAM symbols
    dataModNRx(:,j) = fft(ofdmSymbolRx,N);
    % Carriers channel fixed
    dataModNRxFixed (:,j) = dataModNRx(:,j).*channelCorrection;
    % Recover data carriers
    dataModUsedNRx(:,j) = dataModNRxFixed(unusedN/2+1:N-unusedN/2,j);
end

% Info of the OFDM carriers to a chain of QAM simbols to get data vector
dataModRxFixed = reshape...
    (dataModUsedNRx,size(dataModUsedNRx,1)*size(dataModUsedNRx,2),1);
dataSymbolsInRx = qamdemod(dataModRxFixed,M,0,'gray');
```

```
dataInMatrixRx = de2bi(dataSymbolsInRx);
dataInRx = reshape...
    (dataInMatrixRx,size(dataInMatrixRx,1)*size(dataInMatrixRx,2),1);

end
```

```
Error using RX_CHANNEL_OFDM_ZEROTAIL (line 35)
Not enough input arguments.
```

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```
%-------------------------------------------------------------------------
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%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%-------------------------------------------------------------------------
%   TRANSMISSION OF THE OFDM SIGNAL
%   Simulation of the creation of the OFDM signal from data bits input.
%   Distribution of the bits to create the QAM simbols and place them in the
%   OFDM carriers to form independent OFDM symbols with the cyclic prefix.
%
%   [ ofdm,dataMod ] = TX_OFDM( dataIn,M,N,usedN,CP )
%
%   OUTPUT:
%   ofdm -> Chain of OFDM symbols
%   P -> Power ofdm signal
%   dataMod -> QAM simbols inside the OFDM carriers
%
%   INPUT:
%   dataIn -> Vector of bits
%   M -> Number of simbols of the QAM constellation
%   N -> Number of carriers OFDM
%   usedN -> Number of data carriers OFDM
%   CP -> Length of the cyclic prefix

function [ ofdm,dataMod ] = TX_OFDM( dataIn,M,N,usedN,CP )

k = log2(M);
unusedN = N - usedN;

dataInMatrix = reshape(dataIn,length(dataIn)/k,k);      % Reshape data into binary 4-tuples
dataSymbolsIn = bi2de(dataInMatrix);                    % Convert to integers

dataMod = qammod(dataSymbolsIn,M,0,'gray');
%dataMod = ones(length(dataSymbolsIn),1)*1;

% Data modulated for the used carriers
dataModUsedN = reshape(dataMod,usedN,length(dataMod)/usedN);
% Data added guard carriers
dataModN = zeros (N,size(dataModUsedN,2));

ofdm = zeros(size(dataModN,2)*(N+CP),1);
ofdmSymbol = zeros(N,size(dataModN,2));
ofdmSymbolCP = zeros(N+CP,size(dataModN,2));

for j=1:size(dataModN,2)
    % Insert guard carriers keeping the data modulated in the middle
    dataModN(:,j) = ...
        vertcat(zeros(unusedN/2,1),dataModUsedN(:,j),zeros(unusedN/2,1));
    ofdmSymbol(:,j) = ifft(dataModN(:,j),N);
    % Insert cyclic prefix at the beginning of the ofdmSymbol
    ofdmSymbolCP(:,j) = vertcat(ofdmSymbol(N-CP+1:N,j),ofdmSymbol(:,j));
    ofdm((j-1)*size(ofdmSymbolCP)+1:j*size(ofdmSymbolCP)) = ...
        ofdmSymbolCP(:,j);
end

end
```

```
Error using TX_OFDM (line 30)
Not enough input arguments.
```

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```
%-----------------------------------------------------------------------------
%   Javier Celada Muñoz
%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%-----------------------------------------------------------------------------
%   TRANSMISSION OF THE OFDM ZEROTAIL SIGNAL
%   Simulation of the creation of the OFDM signal from data bits input.
%   Distribution of the bits to create the QAM simbols and place them in the
%   OFDM carriers to form independent OFDM symbols with the zero tail.
%
%   [ ofdm,dataMod ] = TX_OFDM_ZEROTAIL( dataIn,M,N,usedN,ZT )
%
%   OUTPUT:
%   ofdm -> Chain of OFDM symbols
%   dataMod -> QAM simbols inside the OFDM carriers
%
%   INPUT:
%   dataIn -> Vector of bits
%   M -> Number of simbols of the QAM constellation
%   N -> Number of carriers OFDM
%   usedN -> Number of data carriers
%   ZT -> Length of the zero tail

function [ ofdm,dataMod ] = TX_OFDM_ZEROTAIL( dataIn,M,N,usedN,ZT )

k = log2(M);
unusedN = N - usedN;

dataInMatrix = reshape(dataIn,length(dataIn)/k,k);      % Reshape data into binary 4-tuples
dataSymbolsIn = bi2de(dataInMatrix);                    % Convert to integers

dataMod = qammod(dataSymbolsIn,M,0,'gray');

% Data modulated for the used carriers
dataModUsedN = reshape(dataMod,usedN,length(dataMod)/usedN);
% Data added guard carriers
dataModN = zeros (N,size(dataModUsedN,2));

ofdm = zeros(size(dataModN,2)*N,1);
ofdmSymbol = zeros(N,size(dataModN,2));
ofdmSymbolZT = zeros(N+ZT,size(dataModN,2));
zerotail = zeros (ZT,size(dataModN,2));

for j=1:size(dataModN,2)
    % Insert guard carriers keeping the data modulated in the middle
    dataModN(:,j) = ...
        vertcat(zeros(unusedN/2,1),dataModUsedN(:,j),zeros(unusedN/2,1));
    ofdmSymbol(:,j) = ifft(dataModN(:,j),N);
    % Insert zero tail at the end of the ofdmSymbol
    ofdmSymbolZT(:,j) = vertcat(ofdmSymbol(:,j),zerotail(:,j));
    ofdm((j-1)*size(ofdmSymbolZT)+1:j*size(ofdmSymbolZT)) = ...
        ofdmSymbolZT(:,j);
end

end
```

```
%----------------------------------------------------------------------
%   Javier Celada Muñoz
%   Universidad Carlos III, Madrid
%   Grado Ingeniería de Sistemas Audiovisuales
%
%   Final Project
%   Simulation of waveforms for 5G systems
%----------------------------------------------------------------------
%   TRANSMISSION OF THE OFDM DFT-SPREAD ZEROTAIL SIGNAL
%   Simulation of the creation of the OFDM signal from data bits input.
%   Distribution of the bits to create the QAM simbols and place them in the
%   OFDM carriers to form independent OFDM symbols with the zero tail.
%
%   [ ofdm,dataMod ] = TX_OFDM_ZEROTAIL_DFT( dataIn,M,N,usedN,ZT )
%
%   OUTPUT:
%   ofdm -> Chain of OFDM symbols
%   dataMod -> QAM simbols inside the OFDM carriers
%
%   INPUT:
%   dataIn -> Vector of bits
%   M -> Number of simbols of the QAM constellation
%   N -> Number of carriers OFDM
%   usedN -> Number of data carriers OFDM
%   ZT -> Length of the zero tail

function [ ofdm,dataMod ] = TX_OFDM_ZEROTAIL_DFT( dataIn,M,N,usedN,ZT )

k = log2(M);
unusedN = N - usedN;
ZTh = 10;                                         % Zero header
ZTt = ZT - ZTh;                                   % Zero tail

dataInMatrix = reshape(dataIn,length(dataIn)/k,k);      % Reshape data into binary 4-tuples
dataSymbolsIn = bi2de(dataInMatrix);                    % Convert to integers

dataMod = qammod(dataSymbolsIn,M,0,'gray');

% Used carriers now are usedN - ZT because of the ifft size
% The dataModUsedN matrix discards the last QAM symbols
reshapeUsedN = floor(length(dataMod)/(usedN-ZT));       % Number of OFDM symbols to send
disp('Discarded last QAM symbols in ZT-DFTs');
disp(length(dataMod) - reshapeUsedN*(usedN-ZT));
dataMod = dataMod(1:reshapeUsedN*(usedN-ZT));

dataModUsedN = reshape(dataMod,usedN-ZT,reshapeUsedN);  % Data modulated for the used carriers
dataModN = zeros (N,size(dataModUsedN,2));              % Data added guard carriers

ofdm = zeros(size(dataModN,2)*(N+ZT),1);
ofdmSymbol = zeros(usedN-ZTh-ZTt,size(dataModN,2));
ofdmSymbolZT = zeros(usedN,size(dataModN,2));
ofdmSymbolDFT = zeros(N,size(dataModN,2));

for j=1:size(dataModN,2)
    ofdmSymbol(:,j) = ifft(dataModUsedN(:,j),usedN-ZT);
    % Insert zero head and tail in the ofdmSymbol
    ofdmSymbolZT(:,j) = vertcat(zeros(ZTh,1),ofdmSymbol(:,j),zeros(ZTt,1));
    % DFT-s
    dataModUsedNZT = fft(ofdmSymbolZT,usedN);
```

```
    % Insert guard carriers keeping the data modulated in the middle
    dataModN(:,j) = ...
        vertcat(zeros(unusedN/2,1),dataModUsedNZT(:,j),zeros(unusedN/2,1));
    ofdmSymbolDFT(:,j) = ifft(dataModN(:,j),N);
    ofdm((j-1)*size(ofdmSymbolDFT)+1:j*size(ofdmSymbolDFT)) = ...
        ofdmSymbolDFT(:,j);
end

end
```

```
Error using TX_OFDM_ZEROTAIL_DFT (line 29)
Not enough input arguments.
```

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